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A DECISION SUPPORT MODEL FOR
MUNICIPAL SOLID WASTE RECYCLING AT
UNITED STATES AIR FORCE INSTALLATIONS

THESIS

Gregory A. Williams, Capt, USAF

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THESIS

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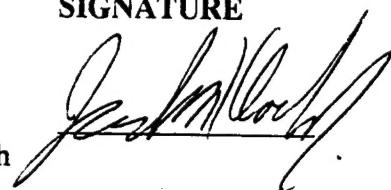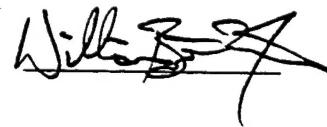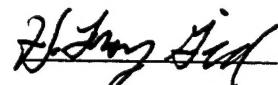
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NAME: Gregory A. Williams, Captain, USAF

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COMMITTEE:	NAME/TITLE/DEPARTMENT	SIGNATURE
Advisor	Jack M. Kloeber Jr., LTC, USA Assistant Professor of Operations Research Department of Operational Sciences	
Reader	Wm. Brent Nixon, Maj, USAF Assistant Professor Department of Engineering and Environmental Management	
Reader	H. Leroy Gill Professor Of Economics Department of Graduate Acquisition Management	

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ABSTRACT

The United States Air Force requires each installation to operate a municipal solid waste recycling program. Two inherently conflicting objectives, waste material diversion and financial result, have been established for the program. Reducing landfill disposal is the primary objective, but the incentive for profit is strong because each installation can retain profits from the program. Installations can be divided into two distinct areas, commercial and residential, based on the waste stream composition and funding. Structuring of the recycling program is often done in an ad-hoc manner. A decision support model was developed to evaluate four methods for each area. The model combines available Air Force data and information from research literature to determine the results of sixteen strategy combinations. The important variables affecting the results are determined through sensitivity analysis. The results are used to establish an efficient frontier of preferred strategies. The frontier illustrates the trade-offs of each strategy. The frontier can be also be used to inform decision makers prior to final strategy selection and determine preference values which would favor a given strategy. The value free analysis provides an objective foundation for presentation to a decision maker with unknown or changing preference values. The model provides valuable insight into the performance of recycling strategies as part of an overall waste management plan.

DECISION SUPPORT MODEL FOR MUNICIPAL SOLID WASTE RECYCLING AT UNITED STATES AIR FORCE INSTALLATIONS

I. Introduction

Background

The management of municipal solid waste (MSW) is a growing concern for the public. Waste generation has steadily increased from 87.5 million tons in 1960 (USEPA, 1988: 1-5) to 323 million tons in 1994 (Steuteville, 1995a:54). Opposition to traditional landfill disposal is also increasing, creating a need for new waste management methods (Platt, 1991:4).

Municipal solid waste is waste from household, institutional, commercial, municipal, and industrial sources (USEPA, 1988). Waste generation rates are increasing, while siting and building new landfills is increasingly difficult. The financial cost of landfill disposal has changed in two ways in recent years. First, increased awareness and regulation have increased costs. Second, they have been accounted for more explicitly, in part because of the realization of their magnitude (Tchobanoglous, 1993:35; EPA 1988:2.E-10,11).

The Environmental Protection Agency has established a hierarchy of management methods for dealing with municipal solid waste (EPA, 1988). In descending order of preference they are:

- **Source Reduction** - preventing waste by redesigning products or otherwise changing societal patterns of consumption, use, and waste generation. The objectives are to reduce the quantity and/or toxicity of waste generated.
- **Recycling and Reuse** (including composting) - removing materials from the municipal solid waste stream and rerouting them through the manufacturing system into new products.
- **Incineration** (preferably in a waste-to-energy plant) - combusting MSW to reduce the volume prior to landfill disposal
- **Landfill disposal** - Burying MSW in selected sites.

Landfills have traditionally been the preferred method of waste disposal. Public opposition to siting of landfills and growing awareness of their potential health impacts in the early 70's led to increased regulation in the 80's and early 90's. Costs of landfill disposal have increased accordingly. The Resource Conservation and Recovery Act (RCRA) created both the legal basis for solid waste regulation as well as greater liability for generators and handlers of waste (Tchobanoglous, 1993:25-26). These changes have internalized many costs associated with waste disposal which were previously external to the system. As the cost of landfill disposal has risen, waste management has become a more visible issue to the public. Nationwide the number of landfills decreased from 8000 to 3377 (Steuteville, 1995a:62). The Air Force, as a customer of landfills throughout the nation, has experienced an increase in costs. The average MSW collection and disposal costs to the Air Force increased by 40 percent, from $48.20 in 1992 to $67.76 in 1994 (AFCESA, 1996).

The increase in the cost of landfill disposal has been one factor in making other MSW management methods more cost effective and more widely practiced. It is now more cost effective to consider use of the other alternatives from the waste management hierarchy. Basic economic principles support this. As the price of a good rises (in this case, landfill disposal capacity), demand for that good will decrease for two reasons. First, substitute goods (source reduction, recycling, incineration) become more competitive since their relative prices are closer to that of the primary good. Second, the demand for the good will decrease because fewer consumers can afford the good (Gwartney, 1995).

Source reduction is the most preferred management method in the hierarchy. It is analogous to pollution prevention; if the use of a material can be eliminated, then the additional management of the material in the form of waste is no longer required. However, source reduction has not significantly impacted MSW generation in the Air Force. Per capita MSW generation in 1994 (the latest available data) is 4.9 pounds/person-day, an increase from the 1992 rate of 4.4 pounds/person-day after a slight decrease to 4.3 pounds/person-day in 1993 (AFCESA, 1996). Some variation may be due to the increased visibility of MSW management, better measurement and records, and more complete reporting in successive years. However, the trend in waste generation appears to be steady if not slightly increasing. The Air Force, like many municipalities, has turned to recycling, the next alternative in the hierarchy, to manage MSW.

Recycling has gained popularity as an alternate method of waste management recent years. The number of programs increased from about 1200 in 1988 to over 7200 in

1994 (Steuteville, 1995a:55). After an initial glut of recovered material catalyzed the development of new processing and manufacturing technology, the markets for recyclable materials developed and profit became part of the picture. Curbside recycling programs now serve over 100 million people in America. Composting has grown from less than 1000 programs in 1988 to over 3200 in 1994. Incinerators have been fairly steady over the same period with just under 150 in 1988 and 155 in 1995, down from 159 in 1994 (Steuteville, 1995a:55). Recycling and composting methods of waste management are more readily accepted by the public.

Executive Order 12780 "Federal Agency Recycling and the Council of Federal Recycling and Procurement Policy" established the federal agency requirement for recycling. Signed by President Bush on October 31, 1991 the order requires "that Federal agencies promote *cost-effective* waste reduction and recycling of reusable materials. (italics added)"(102nd Congress, 1991). The following terms are defined in the Order:

> Recycling: Diversion of materials from the solid waste stream and beneficial use of such materials...which would become or otherwise remain waste, are diverted from the solid waste stream by collection, separation and processing and are used as raw materials in the manufacture of goods sold or distributed in commerce..."

> Waste Reduction: Any change in a process, operation, or activity that results in the economically efficient reduction in waste material per unit of production without reducing the value output of the process.

The goals and objectives for Department of Defense (DoD) recycling policy guidance are to, "Prevent pollution and conserve natural resources on DoD installations by reducing, reusing, recovering, and recycling to divert materials from the solid waste stream..." (DoD, 1993).

In response to Executive Order 12780 and the DoD policy guidance, the Air Force has established a goal for solid waste reduction of 50 percent reduction in landfill disposal from the calendar year 1992 baseline measurements by calendar year 1997 (AFIT, 1995). The Air Force guidance states, "(T)he goal of Air Force recycling is solid waste reduction, pollution prevention, and conservation of natural resources" (USAF, 1994a).

Air Force Instruction (AFI) 32-7080 "Pollution Prevention Programs" requires each Air Force installation to "have a single qualified recycling program" and outlines requirements for organizing and running the program. Some of these requirements are materials included in the program (metals, plastic, glass, used oil, lead acid batteries, tires, high quality copier paper, cardboard, and newspaper), organization of program management, and financial guidance for disposition of proceeds. Installations retain the proceeds from sales of recovered materials to offset the costs of the program. If any profit remains, it is used for health and safety improvement projects and recreation improvement. However, waste reduction is the underlying goal of the recycling program.

Through the recycling program "Each installation will strive to recycle as much of the solid waste stream as possible" (USAF, 1994b). Beyond this, each installation commander is responsible for "determining the best methods to meet the Air Force goals" (USAF, 1994a). This leaves substantial latitude for adapting to local conditions. However, the Air Force's overarching objective remains reducing waste disposal.

State and local constraints will shape the legality and economy of the various waste management options for various materials. The EPA noted this in a 1988 report that states, "[the] National perspective may at times be at odds with local goals" (EPA,

1988). An across-the-board goal or standard may not be appropriate given the wide variations in regulatory, financial, and practical constraints. In this context recycling cannot be a one-size-fits-all-bases program. The variety local regulations and market conditions requires installation-level management of recycling programs to optimize program performance.

A previous thesis, "Decision Support Model for Municipal Solid Waste Management at Department of Defense Installations", focused on MSW management decisions over the entire management hierarchy (Muratore, 1995). Management strategy, modeled using DPL™ decision analysis software, was analyzed to determine the optimal waste management system. It seeks to determine the optimal management strategy by considering all levels of the MSW management hierarchy: source reduction, recycling, composting, incineration, and direct landfill disposal. The output is a recommended proportion of material to be managed through each method. Four criteria are used to evaluate the management strategies: attainment of pollution prevention goals, waste diversion from landfills, economic costs (dollars), and social cost.

Recommendations for future research based on Muratore's thesis include "expand the model to include more specific composting and recycling alternatives... (and) expand the model to include more than the five waste streams used in this model." More detailed modeling of Air Force recycling alternatives should improve Muratore's model, and may provide specific information for the recycling program within the context of MSW management.

Research Problem

The management of installation recycling programs is driven by conflicting objectives of maximizing waste diversion and maximizing revenue. Regular turnover in the manager position is also a problem. One MAJCOM manager stated that installation recycling managers had changed 24 times at 22 bases in his command in one year (Haley, 1995). More detailed modeling of recycling in the context of a MSW management strategy is needed to provide a sound basis for decision making.

Research Objective

Create a decision analytic model of recycling at the installation level. The model will recommend alternative strategies to the decision maker which most support the overall MSW management goals and enhance the MSW management model.

Supporting Objectives

- Determine the basic values and influences of an installation recycling program.
- Determine all significant influencing factors for installation recycling programs.
- Explore the opportunity for the recycling model to provide stand-alone analysis in addition to supplementing the existing MSW management model.

Scope Limitation

This model will consider recycling of municipal solid waste. Hazardous waste is not included. While the proper handling of special wastes such as motor oil, tires, vehicle

batteries, and other materials is important, they are not considered in the model. They are

a small part of the waste stream, and are addressed through other programs in place at

many installations. In addition, the original model by Muratore (Muratore, 1995) will be

used as a framework so the inputs and outputs of the recycling model will support the

larger waste management model.

II. Literature Review

Introduction

This chapter discusses the history and development of recycling. Broader issues of waste management and recycling on a national and global scale are introduced. The development of waste management in the regulations and policies of the Federal Government, Department of Defense, and Air Force are presented. Finally, management and modeling of recycling is presented with particular attention given to decision analysis approaches.

History/Background

Management of municipal solid waste has been an issue for as long as civilized man has lived in one place. Prehistoric civilizations left their waste where it fell, but studies have shown this was usually some distance from the center of the camp (Nixon, 1996a). Some cities evolved from successive layers of dirt covering the accumulated debris on the floors, rising two to five feet per century (Nixon, 1996a). Over time, the cities would rise above the surrounding land.

The industrial revolution created a higher concentration of garbage which required new methods of management. The amounts of waste became too much for the scavengers and limited disposal methods to handle, so centrally organized waste disposal became the norm. The first comprehensive public garbage management system began in 1895 when

Colonel George E. Waring, Jr became New York City Street Cleaning Commissioner (Nixon, 1996a). By 1910, 80 percent of American cities had municipally-run garbage disposal systems (Nixon, 1996a). City dumps developed, and the practice of "sanitary landfilling" (burying garbage in the ground on a large scale) was first practiced in the 1940's in Britain (Nixon, 1996a).

The regulatory evolution of MSW management can be traced to the 1899 US Rivers and Harbors Act, which gave the US Army Corps of Engineers authority to regulate dumping into "navigable" waters (Nixon, 1996b). The Solid Waste Disposal Act (SWDA) of 1965 promoted the implementation of solid waste management systems and new resource recovery technologies. This is the first "regulatory" discussion of post consumer technology (Nixon, 1996b). The Resources Recovery Act of 1970 is an amendment to the SWDA. It shifted the focus from waste disposal to reuse and recycling, including energy recovery by incineration (Nixon, 1996b). The Resource Conservation and Recovery Act (RCRA) was passed in 1976 as a series of amendments to the SWDA. RCRA is the single most important legislation regarding solid and hazardous waste (Nixon, 1996b). The "cradle to grave" liability of waste generators is a critical part of the environmental reforms that have occurred since then. RCRA subtitle D specifically covers solid waste, including MSW. Subtitle D regulations address construction, operation, and closure of landfills. The regulations required improved containment of the waste, leachate, and gas; financial responsibility, and daily operation methods.

The latest regulatory actions are targeted at reductions in the amount of waste being landfilled. California's Integrated Waste Management Act, passed in 1990,

mandates 25 percent diversion from the waste stream by 1994, and 50 percent by 2000 (Nixon, 1996b). BioCycle Magazine's 1995 *State of Garbage in America* report shows that only two states do not have statewide solid waste recycling/reduction goals (Steuteville, 1995a). About two-thirds of the goals are recycling/diversion oriented, including recycling, composting, and source reduction; while the other one-third are waste reduction in terms of volume, generally from a baseline year (Steuteville, 1995a). Bans on material disposal also vary from state to state. All states passed legislation requiring some reduction in the amount of waste disposed in landfills following the EPA's announcement in 1989 to reduce landfill use (Oskamp, 1996).

Much of the recent publicity regarding MSW management relates to the RCRA subtitle D regulation of landfills. Subtitle D has two areas of concern, which led many small quantity landfills to close in the past five years to avoid them. First, increased regulation of operations such as waste handling, what waste can be accepted, and the design of new and closure of existing landfills. Second, the stricter financial responsibility and extended liability for future problems.

Broader National and Global Issues

Policy issues influence recycling at the national and international level. Sustainable Development and Industrial Ecology are two examples of broader philosophies that embrace recycling of MSW. These issues are often very general and can be widely interpreted. They often provide the basis for more specific action to achieve the overarching goals.

Sustainable Development. Sustainable development is defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs (World Commission on Environment and Development, 1989: 43)." Sustainable development presumes an ultimate carrying capacity of an ecosystem, and holds that the appropriate level of activity and resource consumption is that which does not reduce the choices of future generations.

Industrial ecology. Industrial ecology likens industrial systems to natural ecosystems, which are closed loop systems. In natural ecosystems all materials are retained within the system. Output, or waste, from one part of the system becomes input for another part of the system. Industrial ecology strives to make industrial production processes similar to natural ones by seeking to minimize waste, that is unused material. By studying the relationship between natural and manmade systems, a more symbiotic

Energy Input

Closed System: All
materials used within
system - no waste output
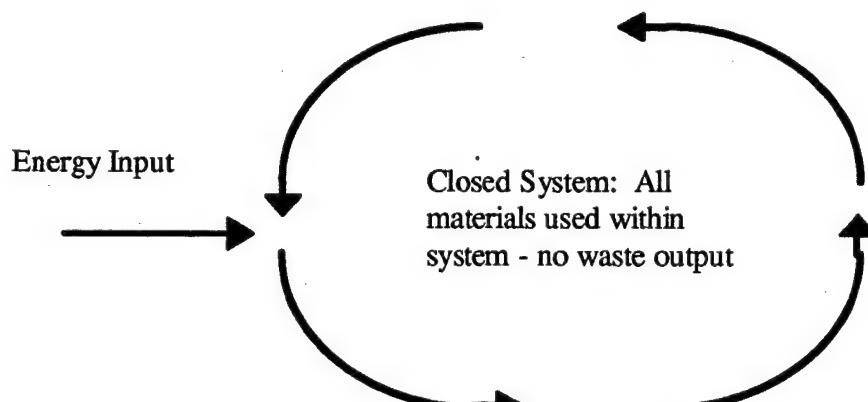
(Adapted from Graedel, 1994:25)

Figure 2- 1 Ideal Ecosystem

relationship can be developed (Graedel, 1994:24). The ideal ecosystem is illustrated in

Figure 2-1. Only energy is input, no waste is expelled. The system uses all "waste" as material for other components of the ecosystem.

Ecologically sustainable organizations. Ecologically sustainable organizations (ESO's) are one response to the issues of sustainable development and industrial ecology discussed above. Ecological sustainability is defined as, "the ability of one or more entities, either individually or collectively, to exist and flourish for lengthy time-frames, in such a manner that the existence and flourishing of other collectivities of entities is permitted at related levels and in related systems (Starik, 1995: 909)." One of the characteristics of an ESO is natural resources are used no faster than either rates of renewal, rates of recycling, or rates that don't exceed the ecosystems regenerative capacity when accounting for technological innovations (Starik, 1995: 917).

The issues above illustrate a fundamental concern at a national and global scale that deal with the interaction of human and natural systems, particularly in the area of natural resource use and depletion. Recycling is one of the primary ways to reduce use of natural materials. Recycling reduces the use of virgin material, which reduces both direct and indirect environmental impacts. Reuse of discarded or waste materials has several benefits. The energy expended to process recycled material is often less than that required to process virgin materials. It saves the consumption of raw materials otherwise required for manufacturing. Reuse of materials also can save refining work required to purify and concentrate raw materials. Aluminum that is recycled can be processed with about 90 percent less energy than creating new aluminum from bauxite (Platt, 1991:11). It also saves disposal capacity. Particularly in the case of municipal solid waste, where up to 75

percent is recyclable (Platt, 1993: 10), the existing disposal capacity can be extended greatly, avoiding the need to site and operate new disposal facilities that are widely perceived as public nuisances.

Municipal solid waste management issues have become increasingly important over the past several years. Waste generation continues to increase as does public opposition to disposal facilities and methods such as thermal treatment (incineration) and landfilling. Traditional methods of budgeting for waste management obscured the actual cost from the public and often from the officials managing the program. Evolution in the management and accounting helped clarify the costs of waste management. At the same time increased awareness of environmental issues led in general and MSW and landfill problems in particular led to increased regulation of the waste industry. The cost of waste disposal increased dramatically.

The average tipping fee nation-wide is $34 per ton. The average regional tipping fees range from $17 to $56 per ton, with a low of $8 per ton in New Mexico and a high of $79 per ton in New Jersey (Steuteville, 1996: 59). Tipping fees are the cost of dumping refuse at a disposal facility; they do not include the collection or handling costs. Tipping fees have become more prevalent as many private companies and government-owned non profit companies began operating their own landfills. The increase in tipping fees nationally and by region is shown Figure 2-2 (Repa, 1996:54). The Air Force's total cost of waste management is also shown in Figure 2-2 for comparison. Tipping fees are only a part of overall MSW management costs. However the tipping fee alone exceeds the Air Force's average total cost in the Northeast region of the United States.
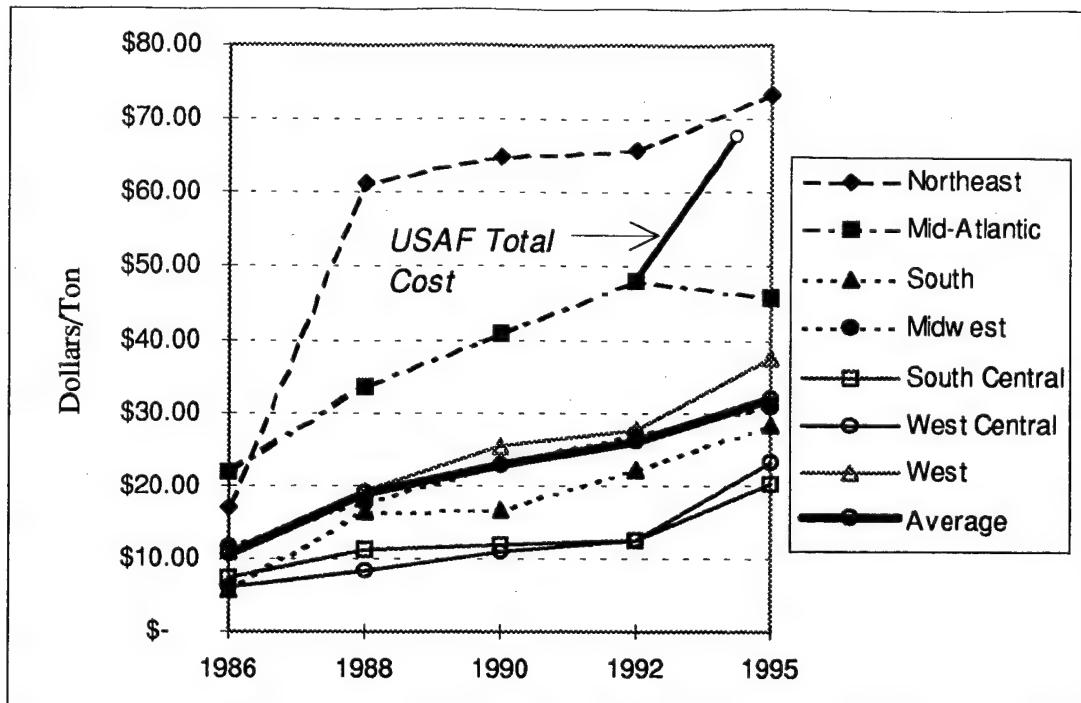
Figure 2- 2 Landfill Tipping Fees

The more explicit costs have exposed the magnitude of traditional funding through taxes.
As the costs have grown and government resources have become scarce, waste
management is one area which has received increased scrutiny in recent years.

User fees have been implemented in many localities. The user (resident or
business) pays a fee for the waste collection service. The fee can be based on weight or
volume. In some cases, the fee is based on the container size. Some communities are
requiring use of standard containers. Allowing more automation in collection. Standard
containers have also been used to ration the amount of refuse discarded. Residents must
pay additional fees for disposing more than their allotted container's volume. One can
imagine that illegal dumping increases in such a system. In such instances, the optimum
solution is to adopt a deposit refund approach. A deposit, charged to the end user, is

refunded when the material is properly disposed. One example of deposit-refund approach is car batteries. The car owner receives a refund when an old battery is turned in at the time a new battery is purchased. An important aspect of deposit refund approach is the fee must be sufficient to motivate the proper disposal or return of the material.

A similar idea is advance disposal fees (ADF). Again the user pays up front, but receives no refund. The money is used to construct and maintain waste management infrastructure. In Florida an ADF was implemented on beverage containers (Woods, 1995: 94). In part, the fee helped offset the cost of disposal and litter consisting primarily of beverage containers. The ADF was also used as an incentive to create recycling demand, similar to the federal governments efforts discussed earlier. The state set minimum recycling levels for plastic packaging and containers. Once these levels of recycling were achieved for certain manufacturers or materials, they were exempted from the ADF. This incentivized the private sector to help build the recycling infrastructure needed to make recycling more feasible. Without a market for the material, recycling is simply separating garbage.

Federal, DoD, and Air Force Implementation

Federal laws and Executive Orders have established the federal agency requirement for recycling. The goals and objectives for Department of Defense (DoD) recycling policy guidance are stated as "Prevent pollution and conserve natural resources on DoD installations by reducing, reusing, recovering, and recycling to divert materials from the solid waste stream..." (DoD, 1993). The Air Force guidance further states, "(T)he goal of

Air Force recycling is solid waste reduction, pollution prevention, and conservation of natural resources." (USAF, 1994a)

The Air Force has developed additional policy guidance for recycling programs, but the guidance leaves substantial discretion to installation personnel in determining program specifics. An across-the-board goal or standard may not be appropriate given the wide variations in regulatory, financial, and practical constraints. However, the Air Force underlying goal is reduction of landfill disposal. Given the lack of specific guidance for base level recycling programs (perhaps for good reason), the identification of important factors and parameters for program management is important. Focusing installation evaluations on the critical aspects of program design will maximize the benefit achieved.

Literature Approaches

The available literature reviewed regarding recycling appears to fall into four categories: public behavior, market forces, material handling, and management/policy. These categories can be grouped into internal (material handling and management/policy) and external influences (public behavior and market forces). The internal factors can be controlled or affected by the recycling program personnel; the external factors are those that cannot be controlled or influenced to a significant degree by the recycling program.

Public behavior literature addresses the motivations for recycling, from altruistic to the financial. The factors affecting public perception of recycling range from ethical values about environmental issues to financial gain (Evans, 1994; Baker, 1995). Public reaction to a recycling program may affect the structure of the program (Stueteville,

1996). Public involvement in the planning process increases program success, particularly in voluntary programs (Folz, 1991a:230). Awareness, personal commitment, and individual responsibility are increased, resulting in higher participation rates (Folz: 1991a:230). Mandatory programs achieve significantly higher participation and material recovery/diversion rates than voluntary programs (Folz, 1991a:230; Oskamp, 1996:76). Other factors that increase recycling rates are curbside collection, provision of receptacles, clear goals, publicity and education (Oskamp, 1996:76).

General trends and statistics about recycling are found in annual feature articles in publications such as BioCycle magazine's "State of Garbage in America" (Stueteville, 1995a and 1995b) and the Waste Age magazine's "State of Recycling in the United States" (Miller, 1995).

Public awareness and support of the EPA's waste management hierarchy (source reduction, recycling, incineration, and landfill disposal) is somewhat inconsistent (Lober, 1996: 138). Many people correctly recognize source reduction as the most effective way to reduce waste in theory, but actions indicate the public participates more frequently and to a greater degree (material quantity) in recycling than source reduction (Lober, 1996: 138). The fundamental lifestyle changes required to achieve significant source reduction are unlikely to occur soon, if ever. Social and institutional factors which encourage recycling, such as visibility and participation peer pressure are not as effective for motivating source reduction (Lober, 1996: 139).

Market forces include the external factors that affect the disposition of the material. The prices of various materials in the secondary market are reported and

discussed in trade publications (Petrush, 1995). A deposit-refund system is found to be preferred when illegal dumping or burning is an alternative (Fullerton, 1995). The deposit refund system is used for items such as car batteries. The deposit encourages proper disposal (by returning the item to a merchant for the deposit refund).

Material handling and internal operations focus on the logistics of collecting, separating, packaging, and marketing of the recyclable material. The amount of recycling and location of a recycling center can be used to determine conditions when recycling will reduce total waste management costs (Highfill, 1994). Collection costs are a large part of the costs in a curbside program. Some programs are changing to drop off collection as a lower cost alternative (Jablonowski, 1995; Gies, 1995; and Boerner, 1994).

Management and policy issues are a bridge between the external and internal factors. The management and policy literature discusses strategies for achieving the goals of the external influences through operational mechanisms of the internal influences. Management and policy may be a way to influence the external factors indirectly via public policy (Levenson, 1993; Parker, 1995). The primary focus of the management literature is internal factors. Recycling is one alternative often discussed for solid waste management (USEPA, 1976; USEPA, 1988; USAF, 1994b). Recycling is beneficial in conserving landfill space. Minimizing the present value of costs of present and future solid waste management (costs of landfills) is one technique used to scope a recycling program (Lund, 1990). The article shows an example where the preferred recycling program recovers only certain materials, less than the maximum possible. At some point it becomes economically

preferrable to landfill waste rather than recycle it based on the respective costs of landfills and recycling.

More specific study of recycling programs has looked at participation rate and influencing factors. Material recovery rate and participation rate are identified as under-utilized success measures (Everett, 1992). Material recovery rate is the amount of material recovered compared to the material available from those participating. Participation rate is the fraction of those eligible who participate in the program. These two rates provide more relevant information to the program manager compared to total waste diverted. The recovery and participation rates help the program manager identify aspects of the program for improvement. High participation (setting out collection containers) and low material recovery may indicate a problem with participants separating materials. Conversely, low participation and high recovery would indicate a participation oriented improvement effort may increase results more.

The EPA identified five measures for comparing options for MSW management (Figure 2-3). Political pressure is difficult to assess Air Force wide; it probably varies widely from base to base. The remaining four criteria - cost, time, budget, and environmental and health aspects - could provide a basis for evaluation of the recycling program as a whole.

- Costs (based on complete accounting)
- Political Pressure
- Time
- Budget
- Environmental and health aspects (EPA, 1988:2.F-2)

Figure 2- 3 Solid Waste Management Evaluation Criteria

The recycling rate can be used to measure a program's effectiveness. The recycling rate is a function of recycling efficiency (how much of the recoverable material is actually recovered) and household participation rate (how many of the eligible households participate). (Butcher, 1995) A case study of Dunsbury, Massachusetts illustrated the town's avoidance of mandatory curbside recycling by developing a well-performing voluntary drop-off program which precluded further mandatory efforts.

The recycling rate is also referred to as the material recovery rate (MRR) (Tchobanoglous, 1993:584). This is generally used to report the effectiveness or performance of the recycling program. The MRR calculation is shown in Equation 2-1.

$$\text{Composition Factor} * \text{Recovery Factor} * \text{Participation Factor} = \text{MRR}$$

where
Composition Factor = Fraction of waste component in total waste
Recovery Factor = Fraction of material recovered by operation
Participation Factor = Fraction of public that participates in recycling program

(Adapted from Tchobanoglous, 1993:584).
Equation 2- 1 Recycling Rate

This calculation can be used to estimate the performance of a recycling program given values for the parameters in the equation. It can also be used to solve for required levels of any one parameter required to achieve a certain recycling rate by setting levels of the other two. For example, one way to achieve a 40 percent recycling rate is by targeting 50 percent of the waste stream composition, ensuring the recovered material is 100 percent pure (no contamination), and achieving 80 percent participation (50%*80%*100%=40%). This example is shown with bold lines in Figure 2-4. This example also illustrates the high

levels of recovery and participation needed to divert significant amounts of material from the waste stream. A graphical representation of material recovery (percent of total) given varying levels of composition and participation factors is shown in Figure 2-4 (assumes 100 percent purity). Only at high levels of both participation and composition of collection is anywhere close to 100 percent of the targeted material recovered.
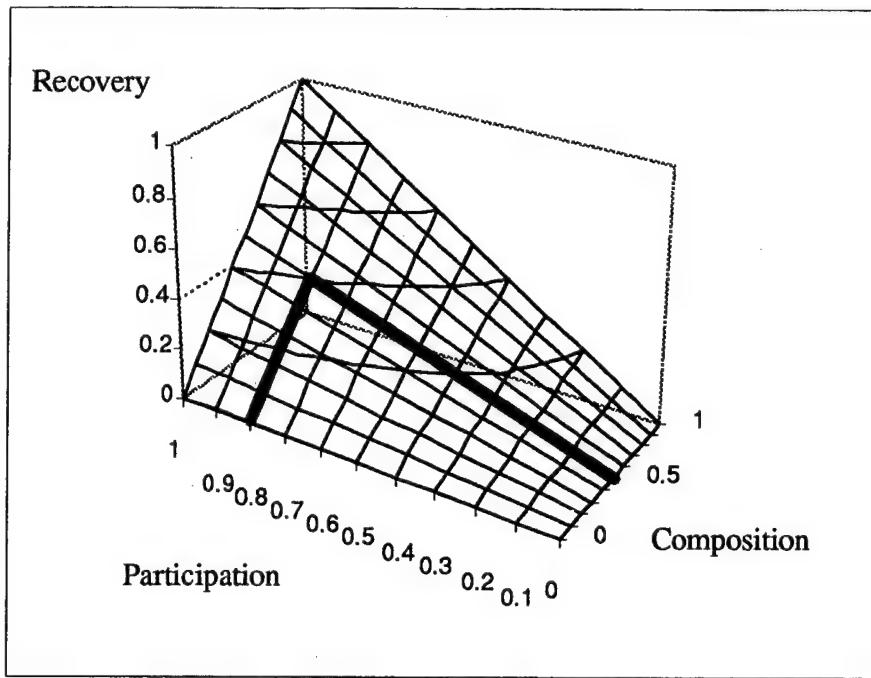
Figure 2- 4 Material Recovery Over Range of Participation and Purity

Modeling Approaches

The EPA's Facility Pollution Prevention Guide outlines process for measuring pollution prevention progress for hazardous waste (EPA, 1992). The three parts of the process are: acquire data, analyze the data, and measure economic results. The last part assumes, "the value of reduced waste production is estimated based on volumes of waste and cost of waste treatment and disposal." (EPA, 1992:49) This method of value

determination appears to be the approach that the Air Force is using, except that there is no significant discussion in Air Force guidance of the avoided costs. The metric of weight reduction could be quickly multiplied by an average disposal cost to determine notional savings, but this would be only an estimate. However, the average costs Air Force-wide distort the variations in cost by region of the country, and thus savings actually realized which depend on the amount of waste disposal avoided in a particular region of the country.

Models of waste management generally fall into two categories: comparative and optimization (Engel, 1990:39). Comparative models help choose between alternatives, while optimization models help management run a given system at the best level. Several commercially available waste management models are presented in "Computer Models For Recycling and Solid Waste Management (Engel, 1990)." The type of model, equipment required, data required, and user-friendliness are presented. The common characteristic of these models is their need for local adaptation. The parameters used are generalized; site specific data is needed to customize the models to local conditions, goals, and limitations.

Other models in the literature focus on the optimization aspect of waste management. One approach uses a multi-attribute goal programming approach to combine local goals and priorities into a model that selects the preferred method from alternatives (Saad, 1991). The process allows the users to determine categories and attributes important to the decision. A normative example is used to illustrate the model. Five evaluation factors, each with several attributes, illustrate the weighting and evaluation of collection and processing alternatives.

Minimizing the present value cost of landfill and recycling efforts was studied by Jay Lund in the paper "Least-Cost Scheduling of Solid Waste Recycling (Lund, 1990)." The cost and recycling effectiveness are combined with the cost savings achieved by extended landfill life to develop a model. The model uses various parameters such as remaining landfill life, recycling options, and types of waste generators to determine an "optimal" level of recycling. This may be less than the maximum level possible, but under the given conditions it is the optimal allocation of resources based on net present value (Lund, 1990).

Decision analysis was applied to management of municipal solid waste in the Air Force (Muratore, 1995). The model considers financial and social costs as well as a goal for waste diversion from landfill disposal. The output is recommended percentages for each of the four waste management methods in the EPA hierarchy (source reduction, recycling, incineration, landfilling).

Modeling efforts address the different objectives of the organization managing waste. Various approaches are used in managing waste; in turn, various approaches to motivating recycling must be considered. Economic aspects may be the priority for some organizations while environmental issues may be more important for others. The decision of how to structure the recycling program is common to both perspectives.

III. Methodology

Decision Analysis Introduction

The decision analysis process steps as described by Clemen (1991:6) are:

- Identify Problem

- Identify Objectives and Alternatives

- Decompose and Model the problem

- Choose the Best Alternatives

- Perform Sensitivity Analysis

- Decide If Further Analysis Needed

- Implement Chosen Alternative

The process is iterative, improving the comprehensiveness of the analysis as each cycle of analysis is completed. Repeated cycles of the process steps will almost certainly lead to changes in the problem structuring. The decision maker's perception of the problem and related issues changes over time. Decision analysis provides a basis for these changes as well as a framework for thinking about the decisions (Clemen, 1991:7)

Identifying the problem clearly and concisely is fundamental to decision analysis. The initial problem may be just a symptom of a deeper problem. A concise, precise problem definition is important. Without this, the wrong problem may be addressed, known as an "error of the third kind" (Clemen, 1991:5).

Identifying the objectives involves careful thought, and can lead to alternatives that may not seem obvious initially. Several objectives may be identified, some may seem contradictory. Decision analysis techniques are just as appropriate in with many objectives as with cases with a single objective. Zeleny's Theory of the Displaced Ideal contends that any problem based on a single aggregate measure involves no decision making, it is simply a measurement exercise to determine the best alternative (however complex the measurement may be). Only multiple attribute problems are appropriate for theoretical consideration as decision analysis (Goicoechea, 1982: 24). Conflicting objectives are an implicit condition of the multiple attribute problems. Many problems that initially appear to be based on a single objective may be decomposed into parts that compose several objectives.

Decomposing and modeling the problem breaks the larger problem into smaller, more manageable parts. These smaller components allow careful consideration of various aspects of the problem such as objectives of the problem or uncertainty in some aspects of the problem (Clemen, 1991:7). Three aspects of modeling the problem are the problem structure, uncertainty, and preferences (Clemen, 1991:7). Modeling of an installation recycling program will be discussed later in this chapter and will involve all three of these aspects.

Choosing the best alternatives is the point of decision analysis. The preliminary stage, or the initial iterations, may be used to narrow the choice of alternatives for the decision maker. Subsequent iterations may use more detailed criteria and analysis to discriminate between more competitive alternatives.

Sensitivity analysis answers the "what-if" questions. Changing one or more parameters in the model may affect the outcome; sensitivity analysis seeks to determine the degree of change in outcome and perhaps preferred alternative due to a change in one of the influencing factor's value. An alternative may be preferred in some circumstances but not in others. Sensitivity analysis may lead to new alternatives or eliminate further modeling of parameters that are insignificant in the analysis, thus simplifying the model.

The decision maker and/or analyst must decide if further analysis is needed. If so, the steps are repeated. This is done until the model and analysis is considered complete. When the decision maker's values and preferences about a problem are fully developed and included in the model, the model is called requisite (Clemen, 1991:22). A requisite model is needed to fully analyze the decision problem. One technique used to assess a model to check if it is requisite is the clarity test (Clemen, 1991:55). The clarity test assumes that one has access to all information needed to determine the outcome of each chance event in the model. The model passes the clarity test if the information allows one to determine what the outcome would be for any event in the influence diagram. No assumptions or judgment should be needed to determine the results beyond those made to define the model parameters.

Once the decision analysis has been completed, the final step is to implement the chosen alternatives. This is simply acting on the decision analysis. It is not actually part of the analysis, but some aspects of implementation (start-up costs, equipment, training, etc) are often part of the analysis. Implementation may be a good measure of alternatives.

Decision Problem Elements

Decisions. The elements of a decision problem are the decision(s) to make, uncertain events, and outcome values. To help frame the problem, decisions must be within the control of the decision-maker and all alternatives must be available. The decision-maker must have the authority to select any alternative. In some cases sequential decisions are required. One decision will affect, or condition, the choices available at the next decision. An example of a sequential decision is a farmer's decision to harvest a crop. Assume the harvest will take one day. Each day the farmer must decide whether to harvest. The next day's choices are conditioned by the previous day's choice; if the crop is harvested, then the farmer cannot decide to harvest the next day. Once the decision to harvest on a given day is made, no decision remains since no harvesting remains to be done.

Uncertain events. Uncertain events are those that the decision maker cannot control, and which may affect the outcome value of the decision. The outcome of those uncertain events may or may not be known before the decision is made. Weather is an example of uncertainty, stock market investing is another. The type of weather or value of a stock tomorrow is not known today. The states of uncertain events are the possible outcomes of the uncertain event. It is important that the stated set of uncertain event states are mutually exclusive and collectively exhaustive. Only one outcome is possible for any given occurrence, and all possible outcomes must be available. For example, the

investment uncertainty can result in gain, loss, or no change. All possible results are available, but only one can occur. If any one state occurs, the other states do not occur.

Uncertainties are often modeled using probability distributions. Some probability distributions are associated with certain types of uncertain events. The binomial distribution is preferred for situations where an event with two dichotomous outcomes and constant probability and independent outcomes is repeated. A classic example of this is the number of heads achieved by flipping a coin ten times. The Poisson distribution is often used for modeling random events occurring over time or space. A normal distribution is used when the uncertainty is subject to many different sources of error. For example, measurement errors may occur due to human error, equipment malfunction, conditions, etc. Many naturally occurring phenomena follow a distribution that can be closely represented with a normal distribution (Clemen, 1991: 249, 253, 259).

Values. Values are the result of uncertain events and decisions. Each combination of decision and uncertain event states must have a value, or a measure of the results of the particular combination of decisions and uncertainties.

The outcome value is the measure after all decisions and chance events have occurred (Clemen, 1991:21). Often, the outcome will have more than one attribute, or measure, such as material recovered and financial result for the recycling problem. The outcome value implies an end point for the analysis.

The planning horizon defines the time in the future when all events have occurred and the result can be measured for the analysis (Clemen, 1991:21). The planning horizon depends on the purpose of the analysis. The events beyond the planning horizon are either

too uncertain or too far in the future to have relevance to the decision(s) at hand. In some cases, the planning horizon may be one of the values studied in the analysis. This is particularly true in pollution prevention projects, where the planning horizon of financial analysis is often found to be too short to reflect long term benefits of many environmental projects (Savage, 1995:7,8).

Structuring Decisions

Two approaches are commonly used for structuring decision analysis problems, decision trees and influence diagrams. Both consider the problem elements (decision, uncertainties and values) but emphasize different aspects of the problem. Decision trees are used when detailed presentations of the decision are needed. Influence diagrams are a more intuitive method of representing the problem. For this reason many analysts find them easier to use with decision makers. The problem structure is shown without too much detail cluttering the diagram.

Consider the decision of structuring of the recycling program. The choice of recycling method will determine the likely, but variable, participation of the base population, which in turn determines the material diversion. The market price of materials sold is uncertain until they are actually sold, so the financial results are unknown as well. This simple problem is used to illustrate analysis tools.

Depending on the use of the analysis, decision trees may be preferred. Figure 3-2 shows a decision tree with one decision and two chance nodes. Each possible combination is shown with the value of that combination. The expected value is

calculated by the value of each outcome state and its probability of occurrence. The decision selects the alternative with the higher expected value. One can easily visualize a decision tree which becomes too large to present clearly because of the many events and uncertainties in even a relatively small problem. The size of the tree expands exponentially according to the number of states for each branch of the tree.
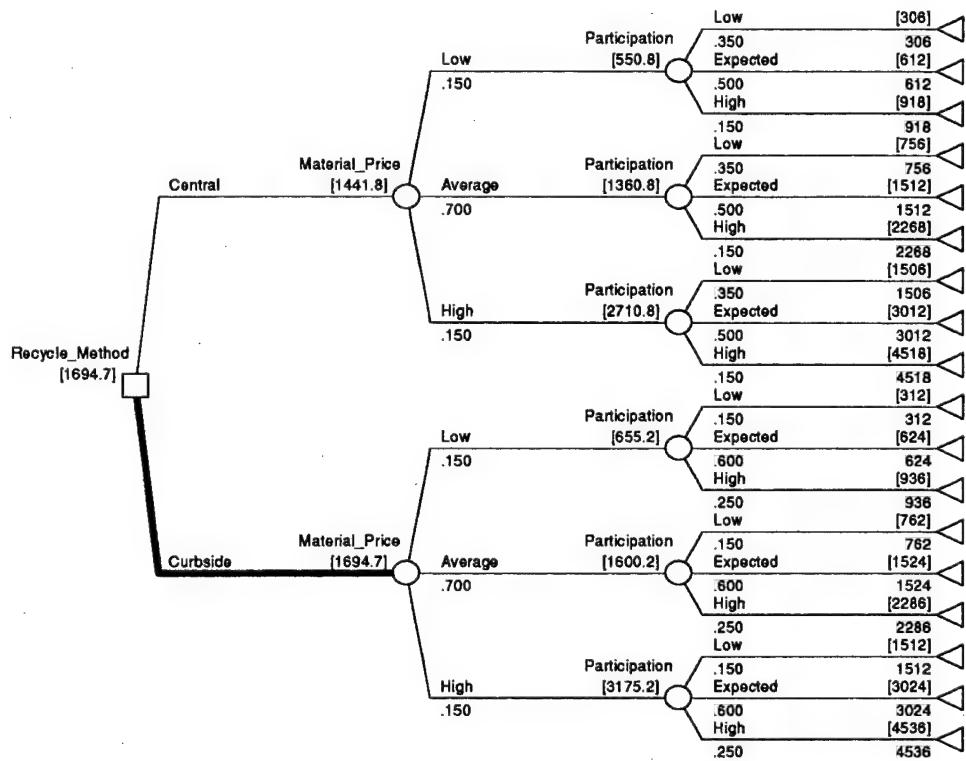
Figure 3- 1 Example Decision Tree

Influence diagrams are useful for presenting the structure of a decision problem while not displaying unneeded detail. Relationships between the various factors of the problem can be communicated more clearly. Influence diagrams are more easily understood than decision trees (Clemen, 1991:54).

Influence diagrams use node symbols similar to decision trees, but connect the nodes with arcs to indicate the relationships between the nodes (Clemen, 1991:22). Squares or rectangles represent decisions (recycling strategy), circles or ovals represent uncertain events (market prices, participation), and rectangles with rounded corners represent value nodes or outcomes (cost, collection method, waste diversion). The participation Sometimes a value node is used to collect results from other nodes. This can be useful for clarifying the structure of the problem to the decision maker. Nodes are connected by arrows called arcs. The arcs indicate the influence of one node on another. A properly constructed influence diagram has no cycles. It is a snapshot analysis of the decision problem.
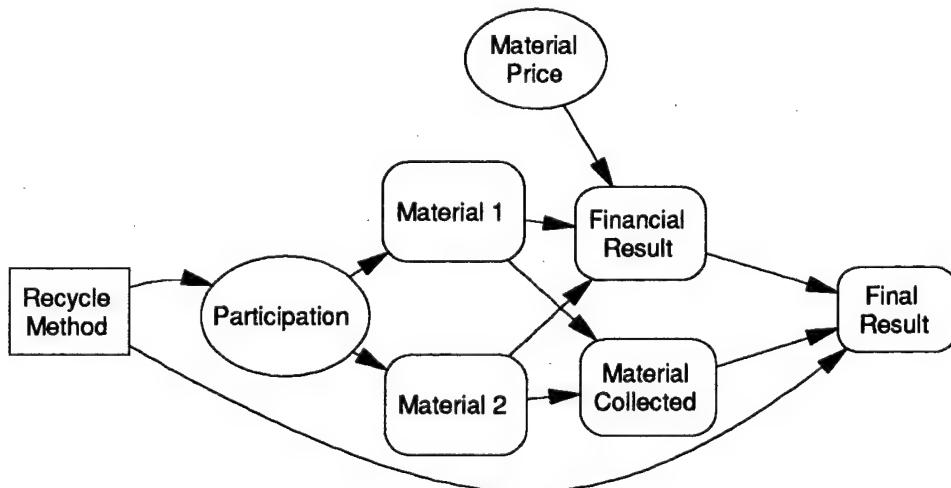
Figure 3- 2 Example Influence Diagram

The influence diagram in Figure 3-3 illustrates the sample problem. The recycling method choice influences the participation, which influences the amounts of materials 1

and 2 recovered. The amount of material collected is the sum of materials 1 and 2. The

financial result is also influenced by the material price. The final result is the combination

of financial and diversion outcomes, and is the basis for selecting the recycling method.

The decision of interest in this thesis is selection of the preferred recycling strategy

for an installation recycling program. Optimum performance is based on two objectives:

waste diversion (from landfill disposal) and financial result (profit or cost).

Recycling Introduction

Recycling of postconsumer materials in MSW involves four distinct phases:

- Recovery of materials from waste stream
- Intermediate processing (sorting and compacting)
- Transportation
- Final processing (Tchobanoglous, 1993: 717)

This thesis will concentrate primarily on the recovery of materials from the waste stream

and intermediate processing; transportation will be studied to the extent that decisions in

this phase will influence the outcome value of the recycling program. The intent is to

model program structuring decisions facing Air Force installation program managers

rather than analyze material handling or transportation alternatives in detail.

The opportunities for recovery of materials from municipal solid waste are shown

in Figure 3-4 (Tchobanoglous, 1993: 829). The recovery of materials may occur at

different points of the disposal process. Material not recovered at some point will

eventually contribute to landfill disposal. Diversion from landfill disposal through material

recovery is accomplished at one of two points in the process, by the generator at the point

of discard (source separated) or by the waste collector at some point during the

collection/disposal stage (commingled collection and material sorting). Within these two

categories are many methods of recycling. Some may combine both categories
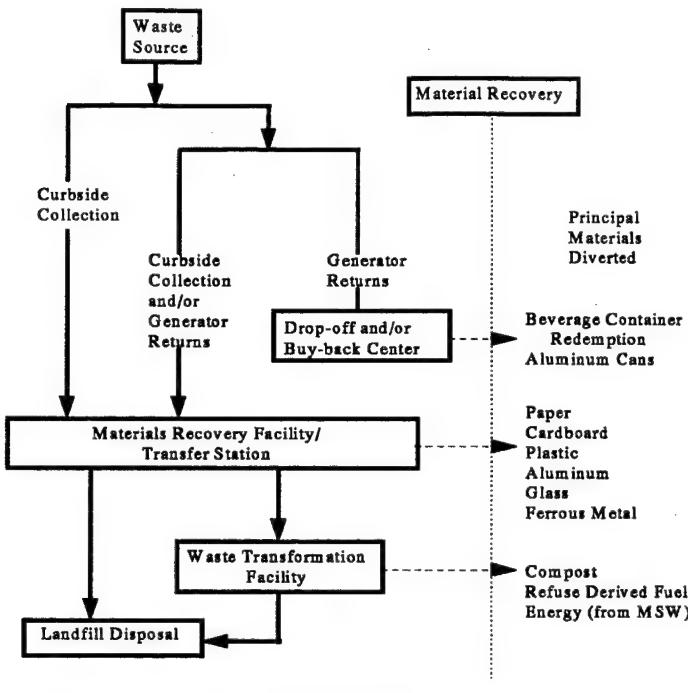
(Adapted from Tchobanoglous, 1993: 829)

Figure 3- 3 Waste Diversion Opportunities

(commingled curbside collection) while others are strictly one or the other (drop off

recycling centers). Between the two categories there are a multitude of combinations of

generator involvement and collection methods. The choices can be narrowed to a few

choices based on the collection method.

Two groups of methods emerge; drop-off (generator transports material to a

collection site) and curbside (material collected at generation site and transported to

processing facility). The groups can be further subdivided by degree of effort required of

3-10

the generator. Higher involvement is required for central drop-off and curbside sorted methods compared to satellite drop-off and curbside commingled methods respectively. The methods that require less effort by the generator are preferred by the generator. The degree of effort required is one factor to consider in designing a recycling program because participation will vary with the degree of effort required (Tchobanoglous, 1993:831).

Modeling Installation Recycling Program

Decisions. The base recycling program manager faces many decisions. Constrained by the guidance from DoD and Air Force, the decisions within the control of the installation program manager narrow to a few. The primary decision is how to implement recycling at an installation based on material collection, separation methods and program work force. The work force choice is generally between an in-house government or a contract work force. It is assumed that most bases will use contract personnel to perform recycling services; this is the case for many bases now (Carper, 1995). Therefore, the decision about workforce may not be very important to the program manager.

The separation and collection decisions are apparent primarily at the point of generation. The generating activity will have varying involvement depending on the method chosen. Collection methods will influence the sorting methods that are preferred. For example, if recyclables are collected curbside, then commingled collection may be more appropriate than source separation by the generators due to the higher participation expected due to greater convenience to the generator.

A typical installation can be separated into two areas: residential and commercial. Residential areas include housing and recreational facilities. Separate funding is used for housing areas, further emphasizing the distinction and helping to clearly define what is residential at each installation. Commercial areas include most "duty" locations such as offices, maintenance facilities, operational facilities, flightlines and other mission related facilities. Waste stream composition will vary between commercial and residential areas (Tchobanoglous, 1993: 41). This variation in waste composition between areas may be a reason to consider different recycling methods for each area.

Another factor within the decision sphere of the program manager is the collection method. Three categories of collection methods are currently used in the US: curbside collection, satellite drop-off centers, and central drop-off centers.

Curbside collection involves collection of recyclable materials at the curb, equivalent to the collection of refuse. The generator of the waste must separate the recyclables from waste prior to collection. Variations include collection of commingled recyclables in one container or separation of materials in multiple containers. Curbside collection usually recovers higher amounts of materials and has higher participation rates than the other collection methods. However, the costs are higher as well. Collection equipment and labor are significant parts of the cost of this method.

Satellite drop off centers are facilities where materials are delivered by the generators to a collection point. They are sited at several locations throughout the collection area to facilitate delivery of the desired materials by waste generators (residents or workers) throughout the community. This type of collection point has containers for

the materials that are recycled. Accumulated materials are collected regularly and transported to a central facility for processing. Satellite drop off centers recover less material than curbside collection because the generator must transport materials to the collection center which results in lower participation. Fewer generators are motivated to participate, and those that do may bring only select materials that are convenient to transport. On the other hand, these centers cost less than the curbside collection for each unit weight of material recovered because part of the transportation and handling costs are borne by the generator. Unless the centers are attended by an employee and/or secured, vandalism is frequently experienced. Also, trash and unrecyclable materials, including some hazardous materials (car batteries, used oil, etc.), are likely to accumulate. These sites can be eyesores unless maintained properly (Reinfeld, 1992:44).

Central drop-off centers are usually collocated with a transfer station, material recovery facility (MRF), or disposal facility. They are similar to satellite collection centers in their reliance on generators to transport material to the collection site. The central location makes them less convenient for the generator, and thus less material is collected. The costs are lower as well. Often the equipment and labor on site to process refuse or other materials is sufficient to process the additional recyclable materials, so some economies of scale are available.

Uncertainties. Two particular uncertainties are important to Air Force recycling programs: participation and price. These two uncertainties have the most significant impact on the program.

Material Price. Price of resold materials is subject to wide fluctuation. Relative stability is anticipated with the opening of the Chicago Board of Trade's Recyclable Materials Exchange (Petrush, 1995; Egan, 1996). Development of formal brokering and other financial practices has introduced some relative control, but prices still vary significantly depending on the quantity, quality, and region of the country. Prices for materials will change independently, paper may be down, but aluminum and cardboard may be at a premium. The price is beyond the ability of any installation to control, so it is uncertain what price the recycled material will bring. However, the reasonable high and low prices can be estimated and used for modeling. Price will affect only the financial result objective.

Participation. Participation is the percentage of people engaging in recycling behavior, defined to be making the recyclable material available to the recycling program as appropriate to the recycling method in use. Participation ranges from transporting the material to a drop-off center to setting out material containers for curbside collection. Participation changes with the recycling method; more people on average will recycle in a curbside program than in a central drop-off program. Participation influences both the financial result and diversion objectives; the material diverted depends on the participation of those involved, and the financial result depends on the amount of diverted material sold.

Values. Two values are the outcome or result of interest: diversion and financial result. These values are the measure of the success of the recycling program.

Diversion. Diversion from landfill disposal is the primary measurement of the success for Air Force waste management. The recycling program at an installation level is often tied to the waste disposal reduction goal. The Air Force's goal is to reduce the amount of waste deposited in landfills to 50 percent of the 1992 baseline by the end of calendar year 1997. The Air Force revises baseline waste figures when an installation significantly changes its mission. The goal achievement can be measured easily by simply dividing the amount of material recycled by the baseline amount of waste to yield the fraction of waste diverted through recycling.

For the purpose of this study we will assume that all waste reduction will be accomplished through recycling (including composting). This may be a moderate simplification, but reflects the prevalent approach to the waste reduction goal. Some installation program managers implicitly assume that recycling is the primary way to reduce waste as opposed to source reduction. Most discussions of recycling and waste reduction focus on recycling almost exclusively as the way to reduce Air Force waste disposal. Air Force Instruction 32-7080 states "Each installation will strive to recycle as much of the solid waste stream as possible (DAF, 1994:7)."

The implicit assumption of recycling as the measure of solid waste reduction is reinforced by the way the Air Force gathers information and measures the reductions. Appendix A shows the data reporting form used by Air Combat Command (ACC). Recycling and incineration are the only categories explicitly measured. The latest available report on the Air Force Solid Waste Survey "identifies trends in the Air Force's progress in meeting its...objective to reduce solid waste disposal...(AFCESA, 1996: ES-1)." The

report contains data on recycling, composting, and waste disposal only. Lack of explicit source reduction measurement focuses waste reduction efforts on recycling methods. Available data shows no change in waste generation between 1992 and 1994, indicating source reduction has not yet achieved significant waste reduction (AFCESA, 1996).

The amount of the waste reduction goal achieved through recycling can be adjusted by the analyst if the decision maker determines the portion of the reduction goal to be achieved by recycling and assess the available alternatives based on that judgment. Previous research indicates that recycling is best used as part of an integrated waste management plan using a combination of source reduction, recycling, and incineration in addition to landfill disposal (Muratore, 1995:60-61; EPA, 1988:4.A-3). Reliance on recycling is further supported by the Naval Air Station Whidbey Island's recycling manager who observed that source reduction alone would not achieve the Navy's goals, that recycling was needed to achieve maximum separation (Brewer, 1996:44).

Financial Results. Financial results can be decomposed into three parts: cost, revenue, and cost avoidance. Cost is the expense of initiating and operating the program. Costs could include collection equipment, containers, labor, sorting and packaging equipment, and publicity.

Revenue is the money received from sales of the recyclable materials. Revenue is calculated by multiplying the amount of material recovered by the market price (usually in dollars per unit weight) of the material. The uncertainty of market prices makes revenue an area of interest. The preferred recycling strategy may change depending on the price

for materials recovered. A high value material (aluminum beverage cans) may justify more expensive recovery methods than a low value material (glass).

Cost avoidance will occur when garbage collection and disposal services are not needed for the amount of material recycled. Cost avoidance may not be a valid assumption for all situations. For instance, at Wright-Patterson AFB the waste removal contract is based on estimated volume of containers on base, the containers are assumed to have an average volume of waste each time they are serviced (Meinerding, 1996). No saving is achieved by disposal of less waste since containers have an assumed volume regardless of actual content. There is no short term way to reduce the contract cost since it is based on estimated amount of garbage rather than the actual amount collected. In this case the cost avoidance would not be an appropriate consideration. (Wright-Patterson does intend to change this method of charging when the refuse contract is renewed). Other bases use weight-based contracts which allow for savings from recycling. Inclusion of cost avoidance will be studied as part of this analysis.

Modeling Values. Several parameters of the recycling program must be known to model the problem. Many of these are based on data available to or known by the program manager. Waste generation (tons/year) may be known or could be estimated based on the population served. Waste stream composition is also useful to know. The composition of the waste stream will be an important basis for deciding how to best recycle material in the waste stream. Other parameters that are needed to evaluate alternatives such as interest rate, time period, and cost avoidance are known or can be

estimated. Many value nodes can be place-holders for modeling parameters that do not

prove to be important parts of the problem.

Model Diagram

The entire influence diagram is shown in Figure 3-5. Enlarged sections of the

diagram follow below (Figures 3-6 through 3-12) with a brief description of the respective

portions of the model. Annotations for the nodes showing many of the calculation

formulas, descriptions, and source citations are shown in Appendix B. The general layout

and approach of the model is discussed in this section. Descriptions of the values in the

nodes is included in the Model Description section of this chapter.
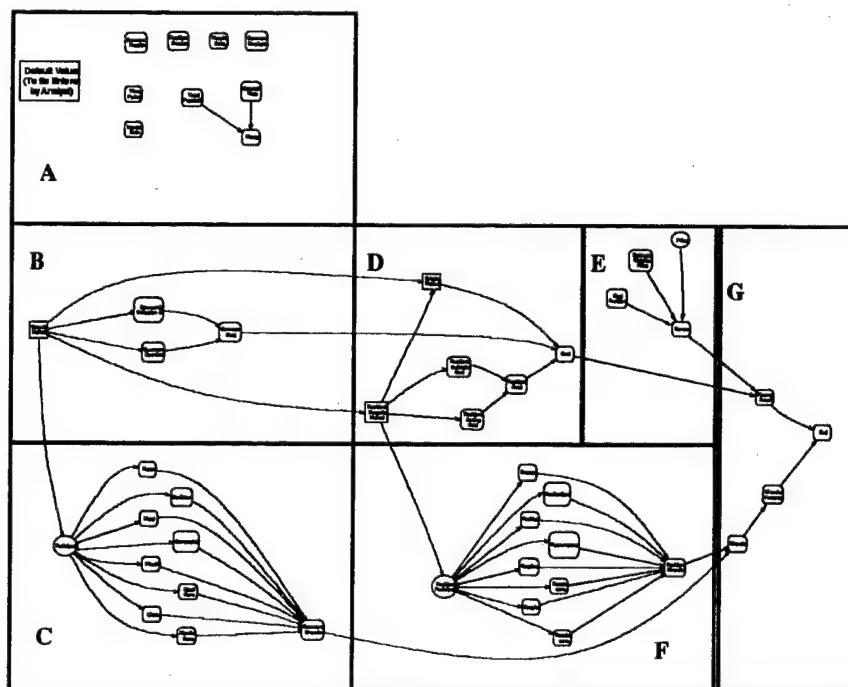
Figure 3- 4 Influence Diagram

Default Value Nodes. Values used in calculations within the model such as total

population (including dependents living in base housing), military and civilian assigned,

number of occupied housing units, time period of analysis (years) and interest rate

(decimal expression; 10 percent = 0.10) are shown in Figure 3-6. Total waste is calculated

by multiplying the total population by the generation rate. Total waste is the basis for the

rest of the model.
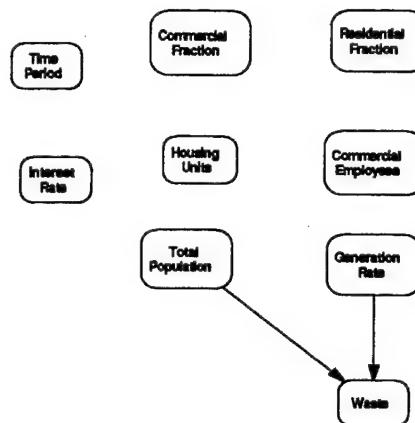
Figure 3- 5 Enlarged Influence Diagram Area A
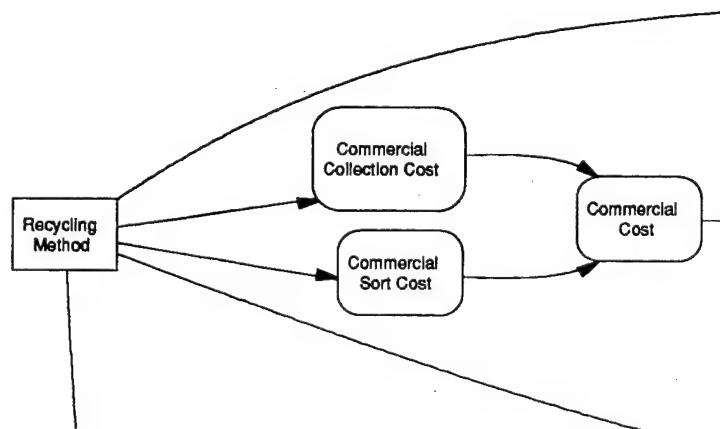
Figure 3- 6 Enlarged Influence Diagram Area B

Commercial Area Method and Cost Nodes. The commercial recycling method
decision and commercial cost nodes are shown in Figure 3-7. The decision selects one of
four recycling methods. This choice influences the cost of collection and sorting activities,
participation, and the capital investment cost. The cost of collection and sorting activities
are summed to calculate total cost of the respective method for the commercial area. The
method choice also influences participation, which is shown in Figure 3-8. Capital cost is
shown in Figure 3-9.
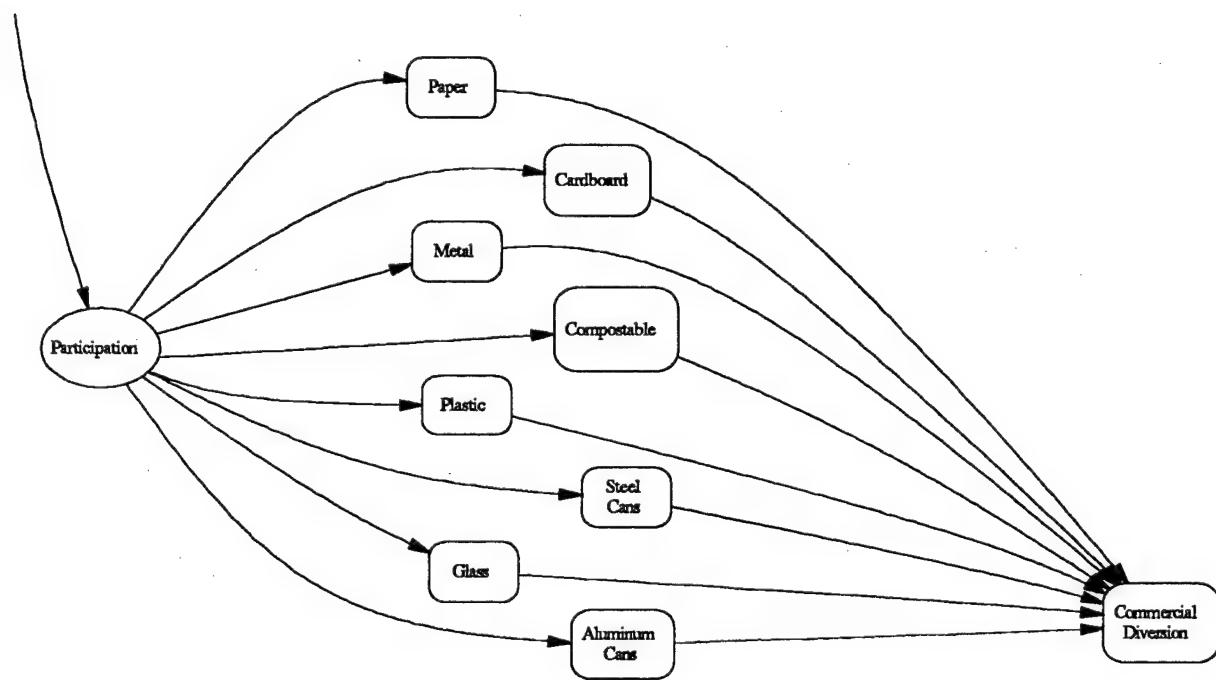
Figure 3- 7 Enlarged Influence Diagram Area C

Commercial Area Material Recovery Nodes. The participation node is influenced
by the commercial recycling method decision, different participation percentages are used
for each method (see Figure 3-16). Material nodes are influenced by the participation.

3-20

Each node calculates the amount of the respective material recovered by the respective recycling method in tons. The material amounts recovered are summed in the commercial diversion node, which is later used to calculate total diversion.

Residential Recycling Method and Cost Nodes, Existing Method Cost Node. The Residential recycling method decision and cost, existing method decision, and total cost nodes are shown in Figure 3-9. The residential recycling method decision selects one of four recycling methods. This choice influences the cost of collection and sorting activities, participation, and the capital investment cost. The cost of collection and sorting activities are summed to calculate total cost of the respective method for the commercial area. The method choice also influences participation, which is shown in Figure 3-11.
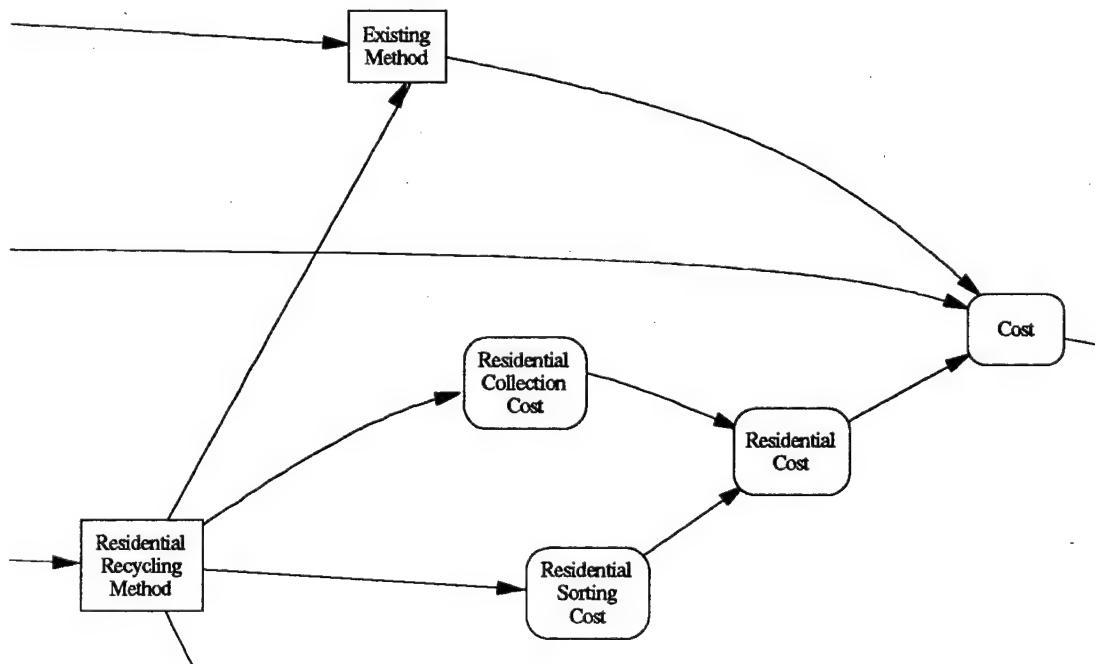
Figure 3- 9 Enlarged Influence Diagram Area D

The existing method decision node is not technically a decision. It uses two alternatives, yes or no, to determine the capital costs of a particular recycling method. The cost of continuing an existing method is generally less than changing to a new method. If an existing method is continued, half of the useful life of equipment used is assumed to remain. The cost of replacement equipment is incurred at one-half the useful life (years) in the future. If a new method is chosen, then the capital cost is incurred at time zero (now) to change to that method. This node is particularly useful to installations considering alternative methods. In this analysis, the existing method is set to "no" to compare the alternative methods equally.

The total cost node combines the residential and commercial area costs into the total cost incurred by the recycling program.
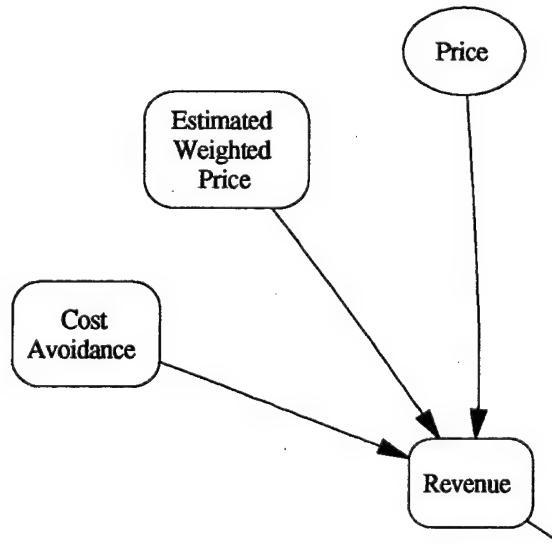
Figure 3- 10 Enlarged Influence Diagram Area E

Material Price Nodes. The revenue and price nodes in Figure 3-10 calculate the amount received for recovered materials. The estimated weighted price (Table 3-1) is

multiplied by the total material diverted. The price node reflects the uncertainty of the particular market price received at any given time, varying from 0.5 to 2 (Lund, 1990). The cost avoidance node is the cost of waste disposal avoided by diverting the material. This is added together with material proceeds to calculate total revenue. This calculation is the same for all options except for the amount of material diverted.
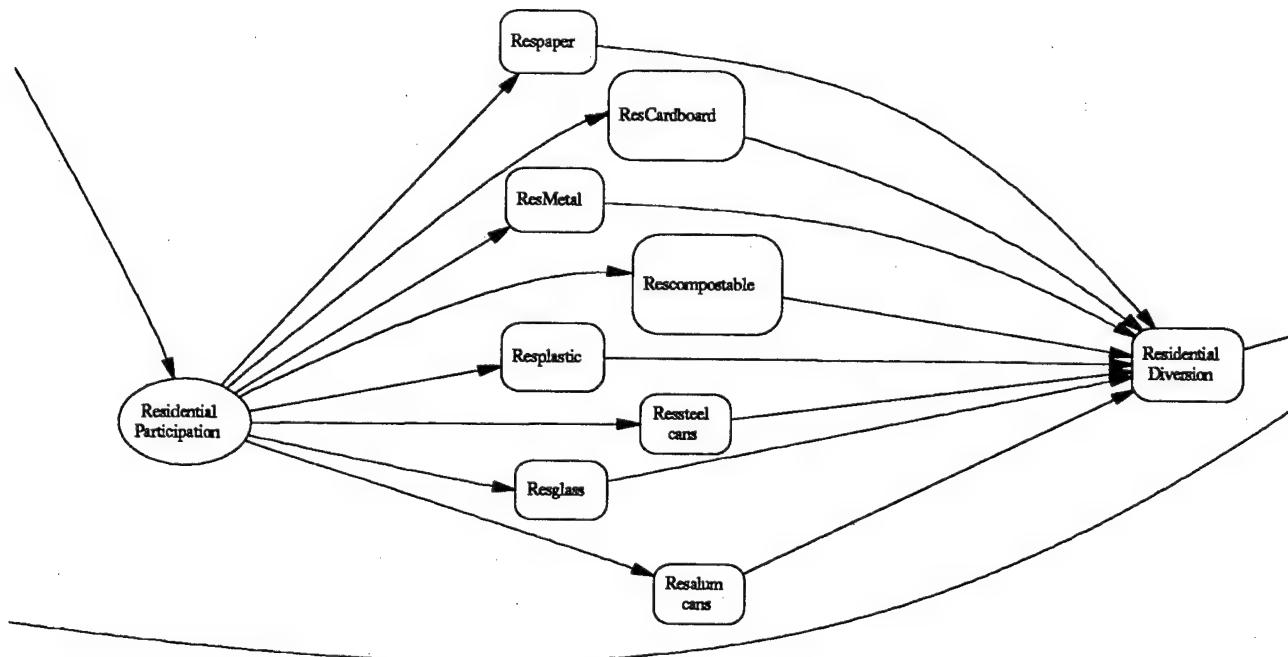
Figure 3- 11 Enlarged Influence Diagram Area F

<u>Residential Area Material Recovery Nodes</u>. Residential area material recovery nodes are shown in Figure 3-11. The residential participation node is influenced by the residential recycling method decision, different participation percentages are used for each method (see Figure 3-16). Material nodes are influenced by the participation. Each node calculates the amount of the respective material recovered by the respective recycling

method in tons. The material amounts recovered are summed in the residential diversion

node, which is later used to calculate total diversion (Figure 3-12).

Outcome Nodes. The final result nodes are shown in Figure 3-12. The financial

result, diversion percentage, and "dummy" end nodes are in this section of the diagram.

The financial result is the annualized income or cost of the recycling program. The

diversion is the percentage of total waste recovered through the recycling program. The
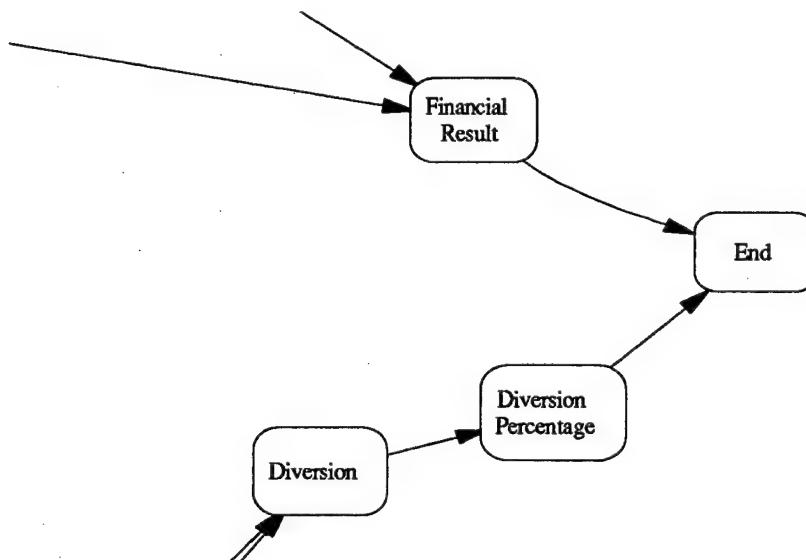
Figure 3- 12 Enlarged Influence Diagram Area G

end node is a dummy node because it is used to bring the diagram to a final node.

Because the results are displayed not as a single value, but as two values, this node is not

needed to complete the analysis. More detailed descriptions and explanations of the

model follow in the next section.

Model Description

The model is developed to represent the situation of most installation recycling program managers. Both commercial and residential recycling methods are the decisions of interest. Some estimates of various parameters affecting the outcome values are available, while others are estimated based on available data. The model is described in detail in the following section based on node type.

Decision Nodes. Three decision nodes are shown in the influence diagram. Two decision nodes represent the major decisions for an installation recycling program, the recycling method for the commercial and residential areas. This distinction is important for two reasons. First, the amount and type of materials available - the waste stream composition - will differ between the two areas (Tchobanoglous, 1993:41). Second, the Air Force (and DoD as well) fund housing operations including waste disposal services, separately from the operational portions of an installation.

Recycling method represents the decision for the commercial area, residential recycling method represents the decision for the residential area. Each alternative within these nodes carries a value for the purity of recovered material. Purity describes the proportion or amount of contamination (other material) or unusable material collected. Contamination decreases the amount of material that can be recycled and may also reduce the price of the material. For example, high-grade office paper sells for $250/ton, but if it contains too much other paper it is classified as mixed paper, selling for $75/ton.

A third decision node, existing program, is included to adjust cost calculations for the existing program infrastructure. This node accounts for the additional cost incurred if

the method is changed from the existing one. Capital costs will vary depending on the existing method and the alternative being evaluated. For example, if a curbside program exists and a change to a satellite program is contemplated, the cost of the satellite collection points is required to establish the new method. However, if a centralized program will replace a satellite program, no additional equipment is required, and there would be no additional cost. This node can be set yes or no for the analysis within the modeling software depending on the analyst's objectives. The model uses this node as a means for installations to customize the analysis to their existing programs. It will not return any particularly useful information for the decision of existing program, the yes branch will always be preferred since it incurs less cost. The existing program node will be set to no so the analysis will consider all options as if they are starting from scratch.

Uncertainty Nodes. Uncertainty is related to probability of some event occurring. In reviewing recycling programs, there appear to be two major areas of uncertainty: participation of generators (which influences the amount of material recovered) and market price of the material sold. Uncertainty nodes are used for both material price and participation.

Material price. Material price can vary by a factor of two over a year (Lund, 1990:188). The material price node reflects this through a uniform distribution from 0.5 to 2 applied to the total money received from all materials. A weakness of this approach is that it presumes all prices change similarly. Variations in the recycled material markets for different materials are not dependent and would likely not vary in this way.

However, the range variation taken over the long term is assumed to be reasonably approximated by this approach.

The market price of recyclable material varies by region of the country and material. Material prices from <u>Recycling Times</u> show price ranges for various materials in November 1995 and October 1996 (Appendix C). The high and low prices are used to calculate average and extreme values used in the model. Calculations are shown in Table 3-1. The model uses the average value of the price over the year, but the outcome value for any of the range of price conditions may be examined in the DPL^{TM} decision policy screen. Prices are included in formulas within the model. They can be easily changed to allow installations to adapt the model for their location and market conditions.

Table 3- 1 Weighted Average Material Price

Material	Recyclable Stream Composition			Price			Wgtd avg revenue per ton collected		
	Commercial	Residential	Weighted	Low	Medium	High	Low	Medium	High
	75% of Total	25% of Total	Average						
Mixed Paper	33.5%	0.0%	25.10%	$0.00	$58.75	$117.50	$0.00	$14.75	$29.49
Res Paper	0	40.8%	10.19%	($7.50)	$21.25	$50.00	($0.76)	$2.17	$5.10
Cardboard	23.7%	7.3%	19.60%	$17.50	$42.50	$67.50	$3.43	$8.33	$13.23
Metal	16.1%	3.4%	12.91%	$0.00	$160.00	$320.00	$0.00	$20.65	$41.30
Compost	13.4%	22.9%	15.77%	($18.50)	($11.25)	($4.00)	($2.92)	($1.77)	($0.63)
Plastic	6.7%	7.9%	7.00%	$60.00	$165.00	$270.00	$4.20	$11.54	$18.89
Stl Cans	2.7%	6.6%	3.67%	$30.00	$60.25	$90.50	$1.10	$2.21	$3.32
Glass	2.7%	10.3%	4.59%	$0.00	$37.50	$75.00	$0.00	$1.72	$3.44
Alum Cans	1.3%	0.7%	1.18%	$950.00	$1,125.00	$1,300.00	$11.17	$13.23	$15.29
Total	100.0%	100.0%	100.00%				$16.22	$72.82	$129.43

<u>Participation</u>. Participation is defined as engaging in the actions required to make recyclable materials available to the recycling program. For curbside collection, this is setting out the appropriate containers for collection. Traveling to the drop-off site and unloading the materials is considered participation for drop-off methods. The

participation node shows the estimated participation distribution for each alternative recycling method. The participation will vary with both method and area as well as the method of determining participation.

A triangular distribution is used to model participation values, with the parameters reflecting the low, high, and median rates for each method. A triangular distribution is a reasonable approximation of participation given the difficulty of measuring participation precisely but the general acceptance of low, high, and average participation levels associated with the methods.

Central drop-off participation is estimated to be 32 percent with a low of 18 and high of 52 percent based on the low, high, and average participation rates for selected materials as shown in Table 3-2 (Reschovsky, 1994: 133).

Table 3- 2 Drop-Off Participation Estimation

Mat'l	DO rate
news	0.182
glass	0.359
plast	0.518
OCC	0.301
metal	0.226
avg	.3172

Participation for satellite drop-off sites is assumed to be 10 percent higher due to the convenience of many locations. Based on the central drop-off participation values, this yields estimated average participation rate of 42 percent with a low of 28 and high of 62 percent based on the low, high, and average values.

Participation rates of curbside commingled programs vary depending on the definition of participation. They have been found to range from 22 percent (every week)

to 90 percent (once in eight weeks) (Oskamp, 1996:80). The average curbside commingled participation rate in this model represents an average value for participation at least half of the time, 61 percent for commingled, and uses the range of values for high and low values of the distribution (Oskamp, 1996:80).

Participation rates for curbside sorted programs vary depending on the definition of participation. They have been found to range from 13 percent (every week) to 77 percent (once in eight weeks) (Oskamp, 1996:80). The average curbside separated participation rates in this model represent an average value for participation at least half of the time, 45 percent for source separated curbside, and uses the range of values for high and low values of the distribution (Oskamp, 1996:80).

Participation rates for the commercial area are 10 percent less than the residential participation shown above. A study of Air Force members' behavior found that 64 percent of members claim to recycle always or most of the time (Holt, 1996: 4-5). It is also noted that few Air Force members believed society is approaching natural limits (Holt, 1996: 5-2), a belief that would motivate recycling behavior. Members may not be strongly committed to preserving environmental quality, rather they may be motivated by non-environmental issues (Holt, 1996: 5-4). This was further reinforced in a group interview, where an Air Force member stated he recycled at home but not nearly as much at work due primarily to his children's interest in recycling (Still, 1996). Lower participation at work than at home may be a fairly common situation, which is reflected in the slightly lower participation rates for commercial areas.

Research comparing residential and office (commercial) recycling supports the assumption of lower participation at work (Marans, 1993:208; Lee, 1994:69). Survey results are shown in Figure 3-6 which show a higher frequent participation response for residential, while occasionally is the most frequent office participation level (Marans, 1993:208). Interestingly the frequent response rate for residential recycling from Marans is the same as that found by a survey of Air Force members (Holt, 1995:4-5). Table 3-3 summarizes the participation rates used in the model.
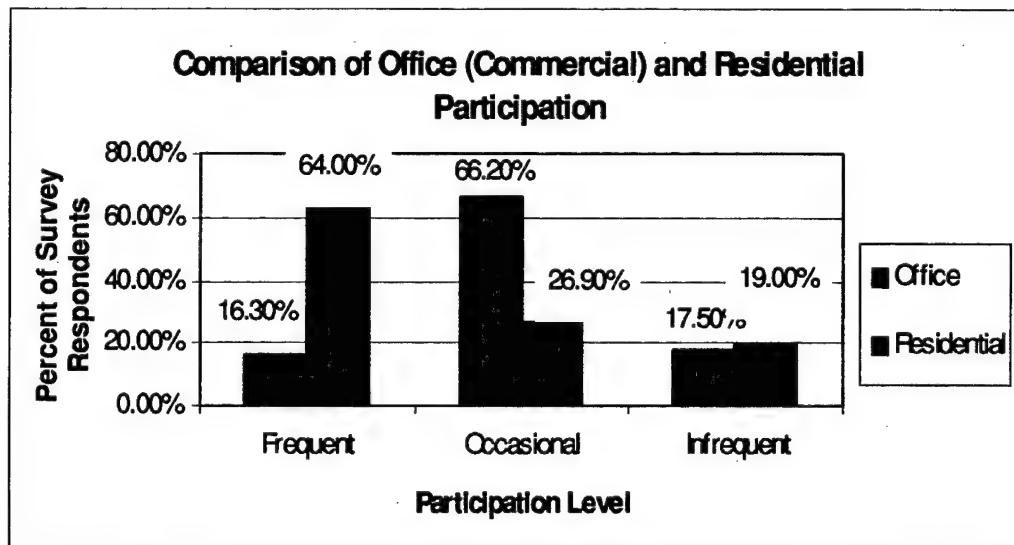
Figure 3- 13 Comparison of Residential and Commercial Participation

Table 3- 3 Participation Rates Used in Model

	Participation Rates					
	Commercial			Residential		
	Low	Average	High	Low	Average	High
Central	0.08	0.22	0.42	0.18	0.32	0.52
Satellite	0.18	0.32	0.52	0.28	0.42	0.62
Curbside Commingled	0.12	0.51	0.8	0.22	0.61	0.9
Curbside Separated	0.03	0.35	0.67	0.13	0.45	0.77

<u>Value Nodes</u>

Value nodes are used to give known information, calculate various aspects of the diagram, collect other values, and show outcome values.

<u>General Values</u>. General values are used throughout the model for various reasons. The total population, commercial employees and housing units nodes contain these respective values for the installation. Commercial employees is the sum of military and civilian employees assigned to the installation. Housing units are the number of occupied housing units at the installation (AFCESA, 1996). Total population is used to estimate total waste generated and is calculated in the waste node. Equation 3-1 is used to estimate total tons of waste generated per year.

Total Population * 1.03 (tons/person-year) = Total Waste Generation (tons/year)
Equation 3- 1 Total Waste Generation

The waste generation rate of 1.03 tons per person per year is based on analysis using data reported to the Air Force Civil Engineer Support Agency from several installations (AFCESA, 1996:A 11-20). The total population was found to be the best predictor of waste generation; better than both the military plus civilian assigned (B) and dependent population (A). Results of a stepwise regression of these variables is shown below in Figure 3-17 indicating total population as the single best indicator, with an R-squared (total variation explained by the regression model) of .6783. Also indicated is minimal improvement to the predictive ability by addition of either or both other variables. Total population was the used as a basis for calculating a per-capita generation rate for each installation based on reported data. The per-capita generation rate is shown in Figure

3-18 in a box and whisker plot used to identify potential outliers. The *box* indicates the

25th, 50th, and 75th percentiles; the *whiskers* indicate the 5th and 95th percentiles.

Table 3- 4 Stepwise Regression Results

```
BEST SUBSET REGRESSION MODELS FOR MSWYR
UNFORCED INDEPENDENT VARIABLES: (A)DEPEND (B)ASSGND (C)TOTPOP
                     ADJUSTED
 P     CP    R SQUARE   R SQUARE   RESID SS    MODEL VARIABLES
 --    -----  --------   --------   ---------   ----------------

 1    289.0   0.0000     0.0000     8.874E+09   INTERCEPT ONLY

 2      5.4   0.6759     0.6783     2.854E+09   C

 2     23.8   0.6318     0.6346     3.243E+09   B

 2     68.5   0.5250     0.5285     4.184E+09   A

 3      4.6   0.6802     0.6850     2.795E+09   A B

 3      7.2   0.6740     0.6789     2.849E+09   A C

 3      7.4   0.6734     0.6783     2.854E+09   B C

 4      4.0   0.6841     0.6912     2.741E+09   A B C
```

Outliers are shown by "*" (potential) and "o" (probable). The box and whisker plot

shows that there are several outliers above approximately 20 lb/person-day.   The

threshold values for the 5th and 95th percentile values (0.8270 and 22.317 lb/person-day

respectively) are shown in Figure 3-19. Using these values, fourteen outliers were

eliminated from further analysis. The total MSW reported for the remaining 130

installations was then compared to the total population using linear regression. The

results indicate an R-squared of 0.6428, showing a slight decrease in predictive ability

(Figure 3-20a). However, the intercept (-917) is counterintuitive. It seems reasonable that zero waste would be the result at zero population. Microsoft Excel™ software's regression tool allows the intercept to be set to zero (Microsoft, 1994:599).
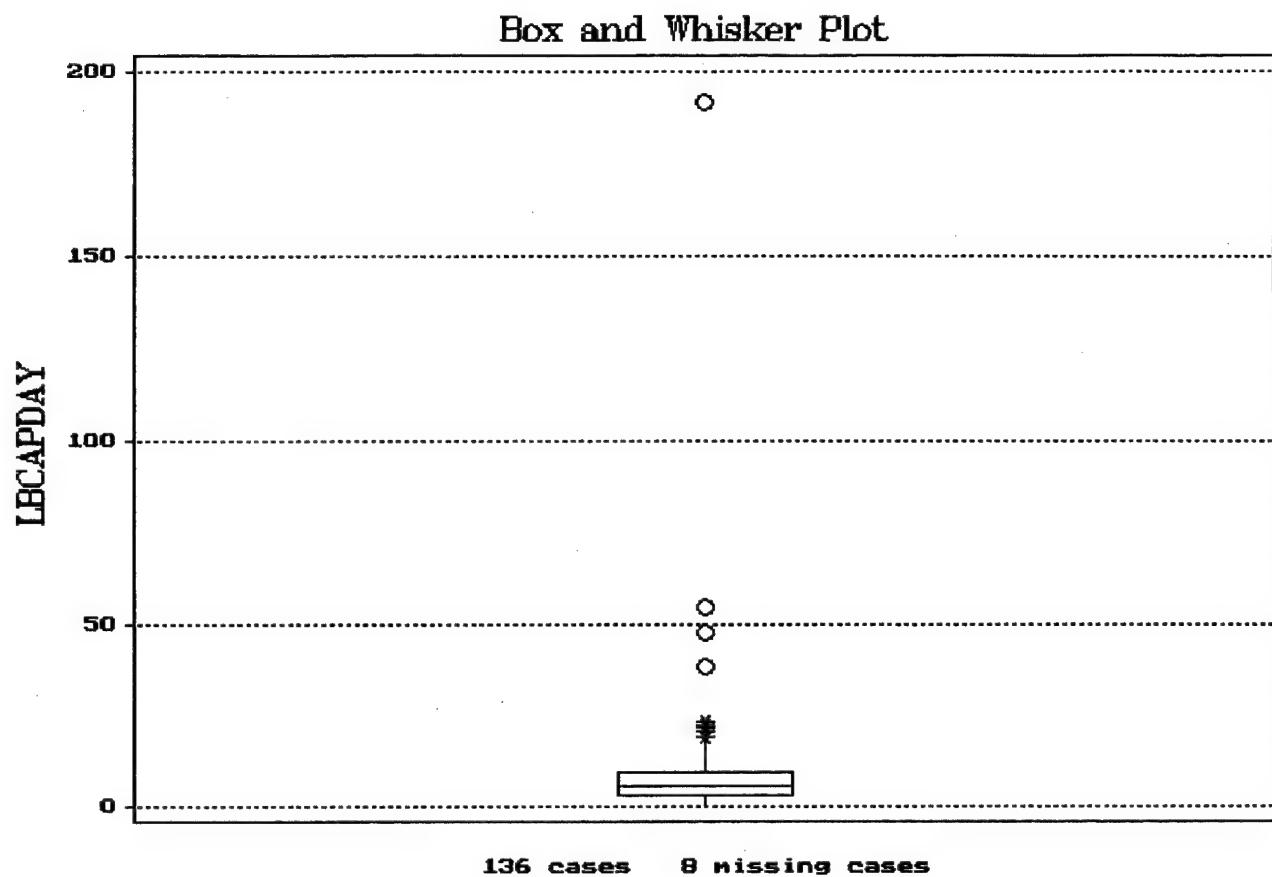
Figure 3-14 Box and Whisker Plot of Per-Capita Generation Rates

Table 3- 5 Outlier Threshold Values

PERCENTILES

VARIABLE	CASES	5.0	95.0
LBCAPDAY	136	**0.8270**	**22.317**

3-33

Regression in Excel shows a similar R-squared (0.6357) when the intercept is fixed at zero, somewhat surprising considering the shift in the intercept from the unconstrained regression (Figure 3-21). This further shows the per capita generation rate is approximately 1.034 (5.66 lb/person-day), somewhat higher than the average of 4.9 lb/person-day in the Air Force data report. The 5 and 95 percent confidence limits of the generation rate are 0.921 (lower) and 1.147 (upper) tons/person-year, or 5.046 (lower) and 6.285 (upper) lb/person-day. Figure 3-22 shows a plot of the regression line and data points.

Table 3- 6 Regression Results - Total Population Waste Generation

UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF MSWYR
PREDICTOR

VARIABLES	COEFFICIENT	STD ERROR	STUDENT'S T	P
CONSTANT	-919.721	578.373	-1.59	0.1143
TOTPOP	1.10772	0.07299	15.18	0.0000

R-SQUARED	**0.6428**	RESIDUAL MEAN SQUARE (MSE)	2.629E+07	
ADJUSTED R-SQUARED	0.6400	STANDARD ERROR OF ESTIMATE	127.39	

SOURCE	DF	SS	MS	F	P
REGRESSION	1	6.055E+09	6.055E+09	230.30	0.0000
RESIDUAL	128	3.365E+09	2.629E+07		
TOTAL	129	9.420E+09			

CASES INCLUDED 130   MISSING CASES 0

If so desired, the model can use a specific quantity for total waste should the calculations not be appropriate. This may be useful for National Guard or Reserve installations that may have significantly different circumstances or for installations with unusual situations.

MSWYR = -919.72 + 1.1077 * TOTPOP   95% conf and pred intervals
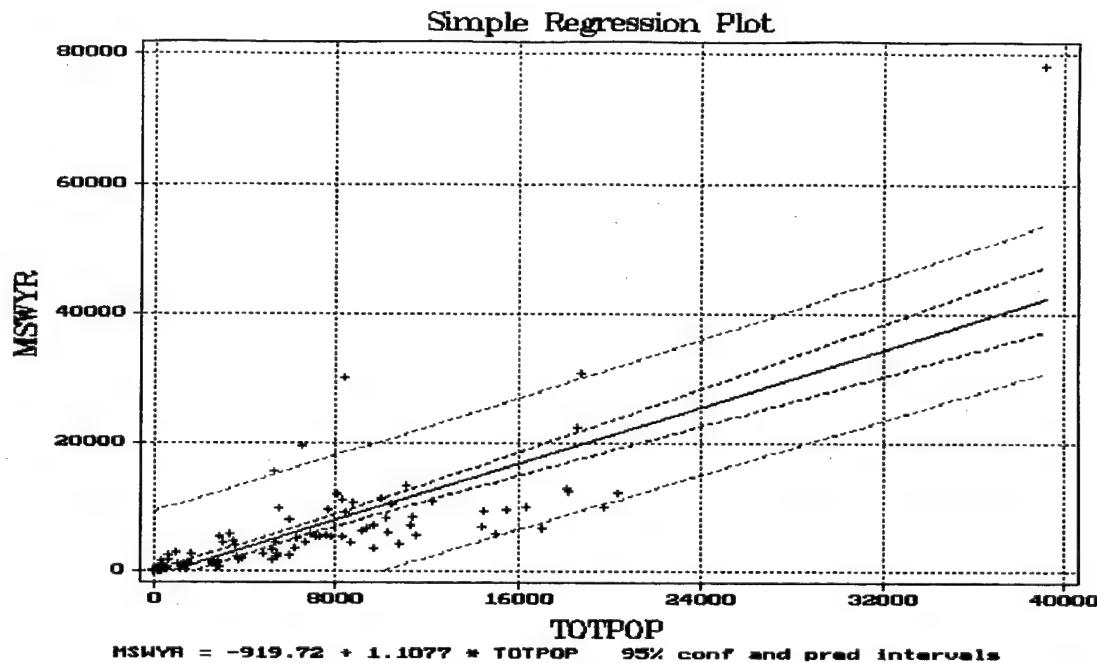
Figure 3- 15 Regression Results - Total Population

Table 3- 7 Regression Results of Screened Data

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.79731							
R Square	**0.635703**							
Adjusted R Square	0.627951							
Standard Error	5157.686							
Observations	130							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	5.99E+09	5.99E+09	225.1063	5.48E-30			
Residual	129	3.43E+09	26601724					
Total	130	9.42E+09						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.000%*	*Upper 95.000%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable	**11.034731**	0.05709	18.12468	2.84E-37	0.921778	1.147685	**0.921778**	**1.147685**

3-35
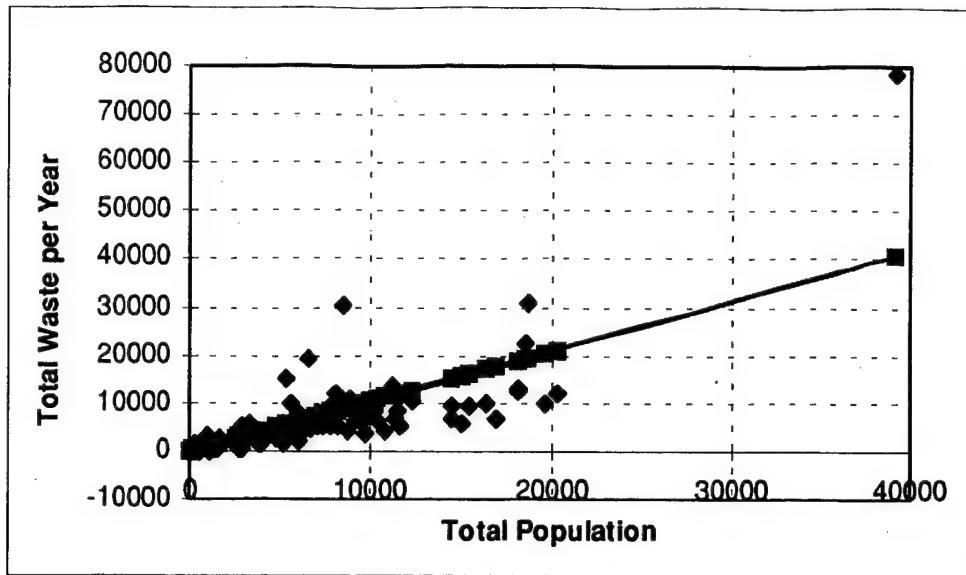
Figure 3-15 Data and Regression Plot

However, the estimation method described here appears to give a fairly good idea of the annual waste generation. The predictive capability of the regression is not very accurate. The prediction interval shown in Figure 3-20b shows the wide range of possible waste amounts generated by any one population. This limitation is considered in the sensitivity analysis presented in Chapter 4 (Figure 4-8).

Commercial fraction and residential fraction nodes divide the waste between these two areas. Based on available generation data, the waste generated Air Force wide is approximately 75 percent commercial and 25 percent residential (AFCESA, 1996:2-5).

Material Values. Each area, commercial and residential, has eight value nodes for eight prevalent materials in the waste stream (paper, cardboard, metal, compostable waste, plastic, steel cans, glass, and aluminum cans). Each material node calculates the maximum

amount of that material theoretically recoverable with each method. The general equation used for each material node is Equation 3-2 shown below:

Total Waste * Area Fraction * Material Fraction * Recycling Method(Purity) *
Material Recycling Likelihood = Estimated Maximum Available Material

Total Waste - Total waste for installation (Tons/year)
Area Fraction - Fraction of total waste generated in commercial(3/4) and
residential(1/4) areas (AFCESA, 1996:2-5)
Material Fraction - Fraction of area's waste constituted by that material
Recycling Method - Purity of material recovered by the recycling method

Equation 3- 2 Material Availability

Table 3-8 shows the recyclable composition for each area. Note that the raw values do not sum to one; there will be some material that is not recovered, other material is simply not recyclable. Estimates are that only about 75 percent of municipal solid waste is ultimately recyclable (Porter, 1996:15). The totals for each area below are reasonably close to the total recyclable amount, so the eight materials presented here are representative the relevant materials for recycling consideration. The normalized values are the fraction of total recyclables available that each material represents. The weighted average shows the combined composition of recyclables from both the commercial and residential areas.

The cost value nodes of collection cost and sorting cost contain the respective cost for each method in each area. The collection costs for central and satellite collection are similar to collection of refuse with conventional containers. The collection costs of curbside commingled and sorted are based on a weighted average of costs of materials, shown in Tables 3-9 and 3-10.

3-37

Likewise the sorting cost is based on a weighted average of the costs of individual

materials. A decrease in cost of 10 percent is deducted from the curbside separated

method to account for savings from reduced sorting of separated materials.

Table 3-8 Recyclable Material Composition

Material	Waste Stream Compostion Commercial		Residential		Wgtdavg
	0.75		0.25		
Paper	25.0%	33.5%	35.6%	40.8%	35.30%
Cardboard	17.7%	23.7%	6.4%	7.3%	19.60%
Metal	12.0%	16.1%	3.0%	3.4%	12.91%
Compost	10.0%	13.4%	20.0%	22.9%	15.77%
Plastic	5.0%	6.7%	6.9%	7.9%	7.00%
Stl Cans	2.0%	2.7%	5.8%	6.6%	3.67%
Glass	2.0%	2.7%	9.0%	10.3%	4.59%
Alum Cans	1.0%	1.3%	0.6%	0.7%	1.18%
Total	74.7%	100.0%	87.3%	100.0%	100.00%

Table 3-9 Weighted Average Commercial Costs

Commercial	Composition		Collection ($/ton)		Processing ($/ton)	
	% of Total Waste	% of Recyclables	Per material	Prorated	Per material	Prorated
Paper	25.0%	33.5%	$ 78.29	$ 26.20	$ 35.06	$ 11.73
Cardboard	17.7%	23.7%	$ 82.13	$ 19.46	$ 47.07	$ 11.15
Metal	12.0%	16.1%	$ 100.00	$ 16.06	$ 100.00	$ 16.06
Compost	10.0%	13.4%	$ 85.38	$ 11.43	$ 106.73	$ 14.29
Plastic	5.0%	6.7%	$ 1,314.00	$ 87.95	$ 201.30	$ 13.47
Stl Cans	2.0%	2.7%	$ 282.82	$ 7.57	$ 72.07	$ 1.93
Glass	2.0%	2.7%	$ 71.18	$ 1.91	$ 54.77	$ 1.47
Alum Cans	1.0%	1.3%	$ 695.33	$ 9.31	$ 157.03	$ 2.10
Total	74.7%	100.0%		$ 179.89		$ 72.21

The revenue node is calculated similarly. A weighted average of the prices of

individual materials shown in Figure 3-13. This represents the money received from the

sale of recovered materials. Prices are based on published values in Recycling Times for

Residential	Composition		Collection ($/ton)		Processing ($/ton)	
	% of Total Waste	% of Recyclables	Per material	Prorated	Per material	Prorated
Paper	35.6%	40.8%	$ 78.29	$ 27.87	$ 35.06	$ 12.48
Compost	20.0%	22.9%	$ 85.38	$ 17.08	$ 106.73	$ 21.35
Glass	9.0%	10.3%	$ 71.18	$ 6.41	$ 54.77	$ 4.93
Plastic	6.9%	7.9%	$ 1,314.00	$ 90.67	$ 201.30	$ 13.89
Cardboard	6.4%	7.3%	$ 82.13	$ 5.26	$ 47.07	$ 3.01
Stl Cans	5.8%	6.6%	$ 282.82	$ 16.40	$ 72.07	$ 4.18
Metal	3.0%	3.4%	$ 100.00	$ 3.00	$ 100.00	$ 3.00
Alum Cans	0.6%	0.7%	$ 695.33	$ 4.17	$ 157.03	$ 0.94
Total	87.3%	100.0%		$ 170.85		$ 63.78

Table 3-10 Weighted Average Residential Costs

the materials (Petrush, 1995; Egan 1996). High and low prices from November 1995 and

October 1996 were used for extreme values to establish the average prices for the year.

The recyclable stream composition is used to derive a weighted average price per ton of

recyclable material collected.

The cost avoidance node represents the costs of disposal avoided by recovering

materials such as tipping fees, transportation, and refuse collection costs. Some of these

costs, such as transportation, are also incurred by the recycling of materials. However,

some costs such as tipping fees at landfills and transfer stations are completely avoided

and therefore can be appropriately counted as savings achieved by recycling. This node is

included for analysis of the significance of cost avoidance in the calculation of the financial

results. The baseline scenario will have cost avoidance equal to the average national

tipping fee (see Figure 2-2), but can be changed to adjust for local conditions.

Outcome Values. The outcome nodes are simply value nodes that show the

outcome values of interest. The outcome nodes are financial result and diversion

percentage. Financial result is the profit or loss for the strategy. Installations may retain

profits from recycling programs, which provides some incentive to operate a profitable program. The financial result is calculated by subtracting the cost from revenue.

Diversion percentage is the amount of material recovered (diversion node) divided by the total waste generated. Again, the assumption that all waste reduction will be achieved through recycling, so the diversion percentage indicates progress towards the Air Force goal of 50 percent diversion from landfill disposal.

Analysis Scenarios

Three scenarios were established for analysis: baseline, optimist, and pessimist. The parameter values used in each scenario are summarized in Figure 3-26. The baseline scenario uses average or most likely values for the parameters. It is intended to reasonably approximate most installations and will be the basis for most of the analysis. The optimist and pessimist scenarios are used to illustrate the results of extreme the extreme values (price, cost, interest rate, etc.) in several different parameters simultaneously. The optimist scenario uses the favorable values for all parameters; low costs, high prices, low interest rates, etc. This scenario will illustrate the best case results that may reasonably be expected in the most favorable situations.

Table 3-11 Scenario Values

	Baseline	Optimist	Pessimist
Generation Rate (Tons/person-year)	1.03	1.15	0.92
Interest Rate	10%	5%	15%
Commercial Fraction	75%	50%	90%
Time Period (Years)	8	20	20
Commercial Collection Cost	$ 179.89	$ 127.45	$ 358.67
Commercial Sorting Cost	$ 72.21	$ 43.70	$ 126.86
Residential Collection Cost	$ 170.85	$ 137.85	$ 269.13
Residential Sorting Cost	$ 63.78	$ 41.06	$ 138.02
Cost Avoidance	$ 32.19	$ 67.76	$ -
Material Sale Price	72.82	129.43	16.22

Conversely, the pessimist scenario uses the least favorable values for all parameters; high costs, low prices, high interest rates, etc. This scenario will illustrate the worst case results that may reasonably be expected in the least favorable situations. The multi-parameter sensitivity analysis will give additional insight into the range of possible outcomes. The results and analysis of the modeling effort and the relative change depending on the three scenarios are presented next in Chapter Four.

IV. Finding and Analysis

Introduction

This section discusses the findings from the research and modeling efforts. The modeling results of the baseline scenario are presented. The sensitivity of these results are examined and lead to the analysis of two alternative scenarios. Finally, the value of the study to the installation recycling manager is discussed.

Baseline Results

The results of the baseline scenario (see Table 3-11) are shown separately for diversion and financial result. The strategy maximizing diversion conflicts with the strategy maximizing financial result; some tradeoff is implicit in the selection of the recycling strategy. The preferred strategy combination is central drop off for both commercial and residential areas for best financial result, and curbside commingled for both commercial and residential areas to maximize diversion. The decision policy recommendations, indicated by bold lines in the tree diagram, are shown in Figures 4-1 and 4-4. Cumulative risk profiles for the respective outcome values are shown in Figures 4-2, 4-3 and 4-5, 4-6 following the financial and diversion decision policy figures respectively. The cumulative risk profiles compare only the commercial area methods; the residential method decision is not changed for any of the commercial strategies. Consistent residential method choice is illustrated in Figure 4-1 by displaying the residential recycling decision branching from the curbside commingled commercial

method. The results for diversion are similar, curbside commingled method is favored for the commercial area. The second cumulative risk profile (Figure 4-6) compares the residential methods based on the preferred commercial method.

The cumulative risk profile indicates the cumulative probability of achieving a certain outcome value or less. When maximizing the given objective, the best alternative is that closest to the lower right or the graph. Points lower and to the right of others on the cumulative profiles indicates lower probabilities of achieving low results relative to other alternatives. The slope of a strategy risk profile can indicate the uncertainty, or risk, of that alternative. A steep profile indicates little change over a broad range of uncertainty; a shallow slope indicates greater change of the outcome value over the range of uncertainty. The risk of an alternative can also be assessed from the range of values over which that alternative's outcomes occur. The larger the range of possible results, the more variability in the result and more risk associated with that alternative.

Dominance can be interpreted from cumulative risk profiles. Deterministic dominance is the stronger type of dominance; when the worst case of one alternative is better than the best case in another alternative (Method 1 vs. 4 in Figure 4-2). No matter what the outcome, a deterministically dominant alternative will always be preferred to the dominated alternative. Stochastic dominance is the less compelling type, referring to parallel risk profiles that do not intersect, but overlap in the outcome value. One alternative's outcome is always preferred at any given probability, but the worst case outcome of the dominant alternative is not better than the best case outcome of the dominated alternative (Method 1 vs. 2, Figure 4-2).
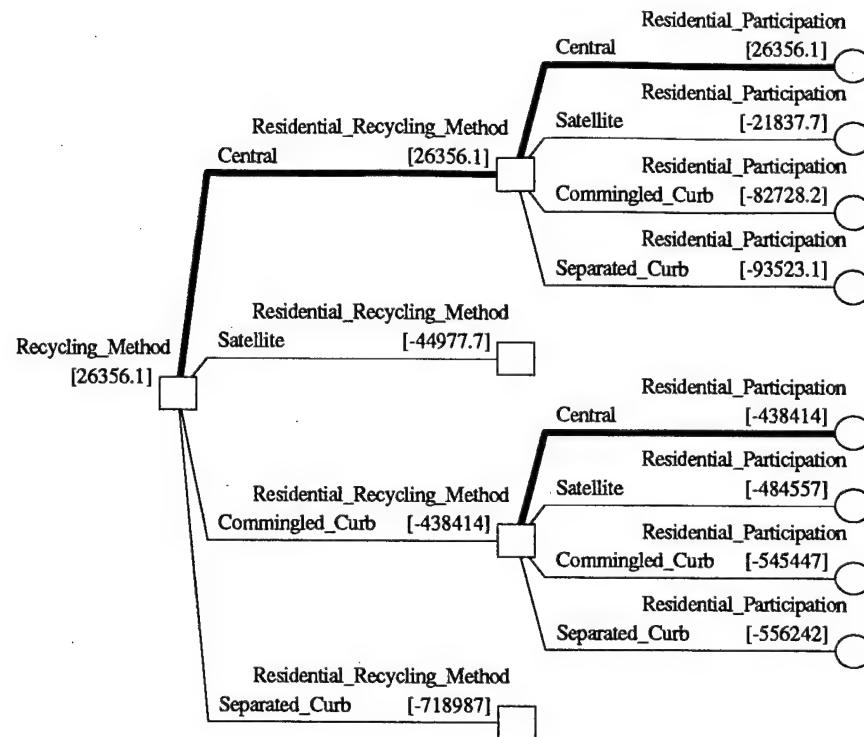
Figure 4- 1 DPL Decision Policy - Financial Result (Baseline Scenario)

Cumulative Probability of Financial Result
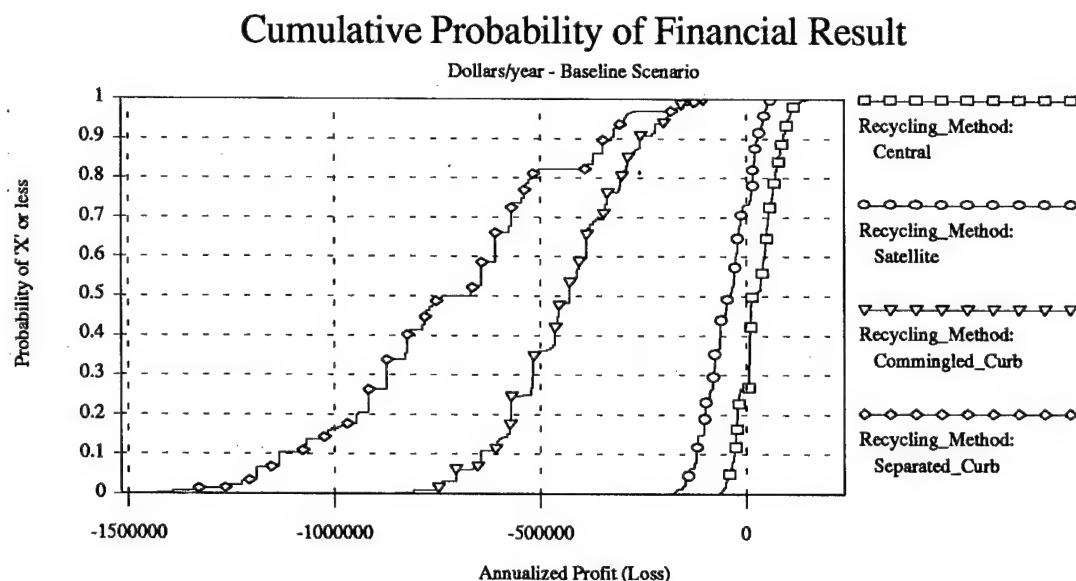
Figure 4- 2 Cumulative Financial Result (Baseline Scenario)

Cumulative Probability of Financial Result
Dollars/Year - Baseline Scenario
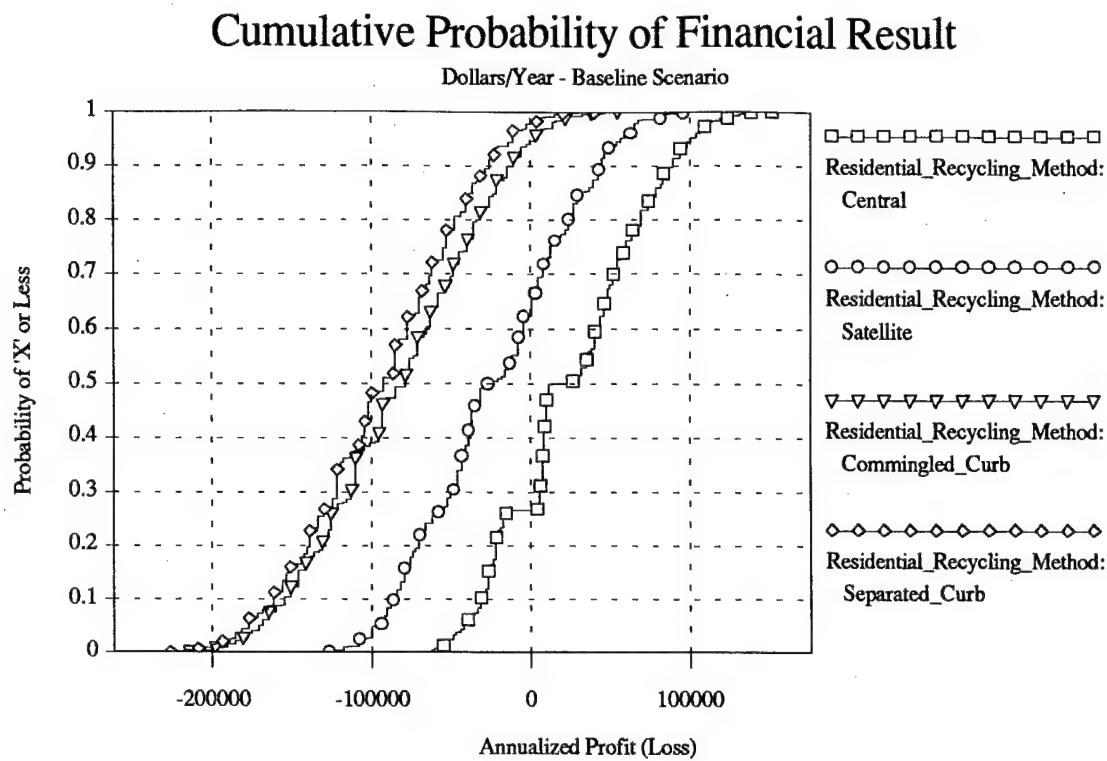
Figure 4- 3 Cumulative Financial Result of Residential Alternatives
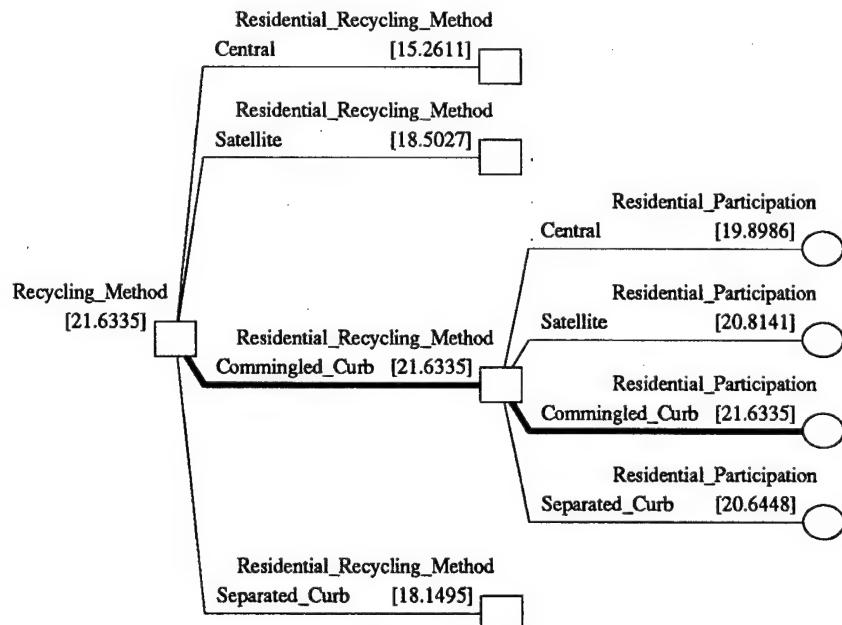
Figure 4- 4 DPL Decision Policy - Diversion Baseline Scenario

Cumulative Probabilty of Diversion Outcome

Commercial Strategies with Residential Commingled Curbside
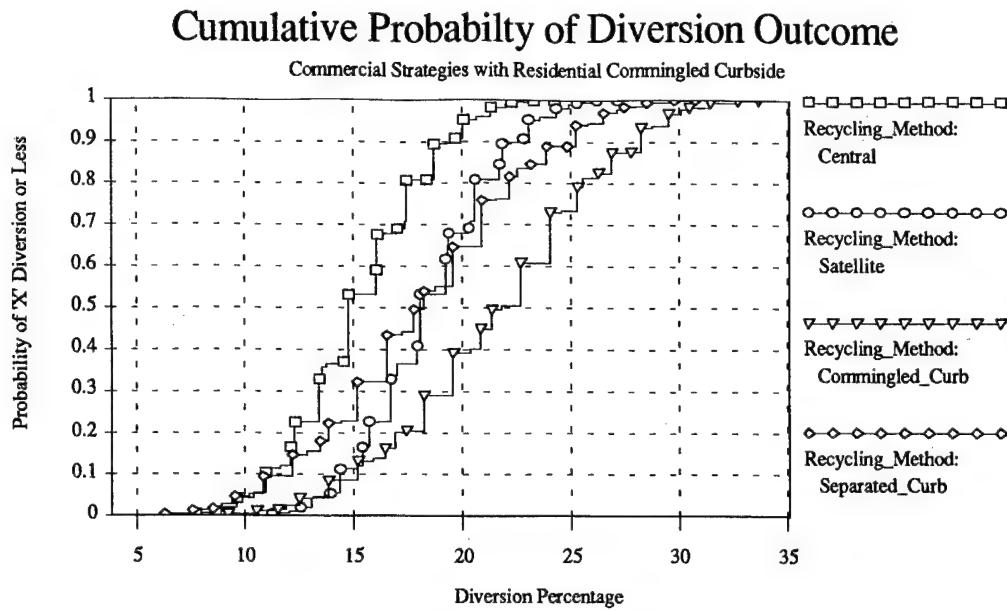
Figure 4- 5 Cumulative Diversion (Baseline Scenario)

Cumulative Probability of Diversion Outcome

Residential Methods
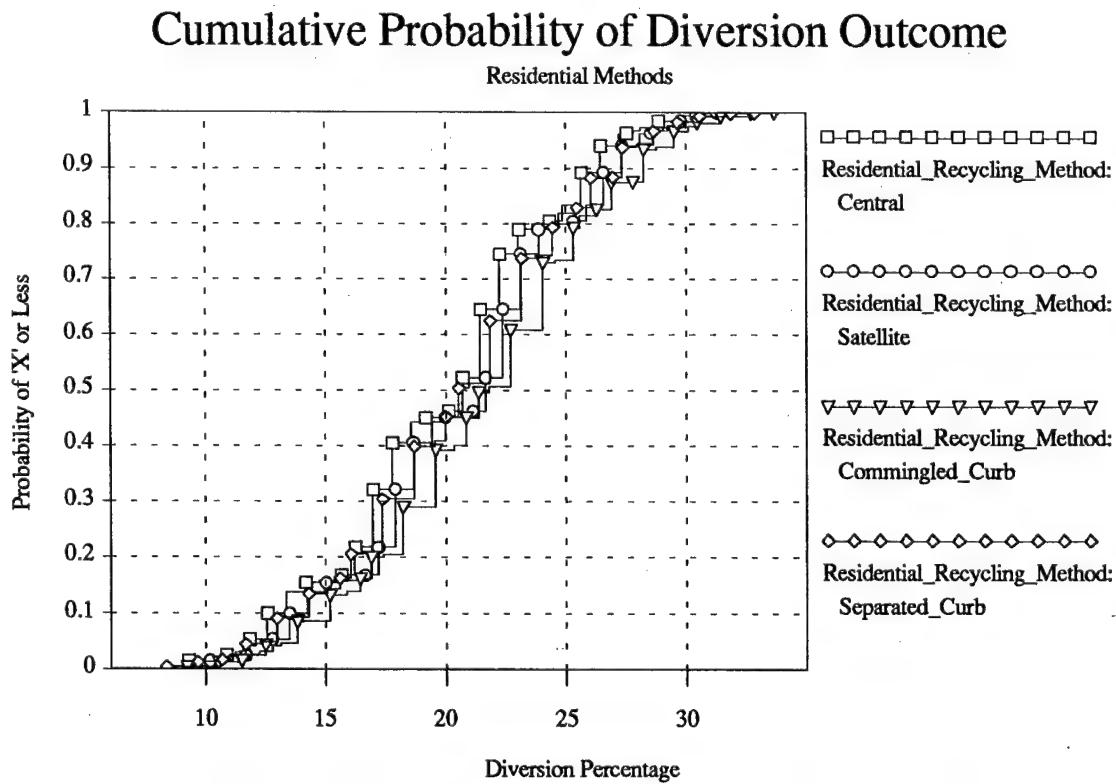
Figure 4- 6 Cumulative Diversion for Residential Alternatives

Financial Result. The cumulative risk profiles for financial result in Figures 4-2 and 4-3 show two distinct slopes. For commercial selection the central and satellite drop-off strategies have steep slopes, indicating less change in the financial result over the range of possible outcomes. The two curbside strategies have a shallower slope and span a greater range of values indicating greater variation in the result or a greater risk of outcomes significantly different than the expected value. Also readily apparent is the clear stochastic dominance of the central drop-off method over all others, and the deterministic dominance of the central drop-off method over both curbside methods. The satellite drop-off method also clearly dominates the two curbside methods based on financial result. The curbside methods have no observed dominance.

For financial results of residential options, the commercial decision is locked on central drop-off. Figure 4-3 shows the residential risk profiles. There is no deterministic dominance for residential strategy, but the stochastic dominance of all other methods by central drop-off still holds. Satellite drop-off stochastically dominates both curbside methods, and curbside commingled stochastically dominates curbside sorted. The preferences established for commercial financial result hold for residential financial result as well.

Diversion Results. The risk profiles for diversion more closely parallel each other, indicating that all the strategies are affected in similar ways by uncertainties (Figures 4-5 and 4-6). The range of extreme values may be of use to a decision maker in distinguishing between alternatives, particularly if there is a threshold value that cannot be exceeded (minimum diversion of X%). If 10 percent were the minimum acceptable diversion, then

curbside methods may be slightly risky; there is a small chance that they may divert less than 10 percent. If the minimum acceptable diversion is 15 percent, then risk of falling below the goal is higher. The central drop off method has a probability of over 0.5 of not achieving 15 percent diversion. This information is very useful to the decision-maker.

Further analysis of the two objectives (financial result and diversion) identifies the significant variables that affect the outcomes. Sensitivity analysis of the baseline scenario will show the variables having the greatest impact on the outcome. Tornado diagrams are used to show the relative impact of each variable on the overall result. The most significant values influencing financial results are shown in Figure 4-7. The estimated price is the most significant with respect to financial result. The other two significant values are total population and cost avoidance. The generation rate, commercial fraction of total waste, and time period are the next most influential, but clearly less so than the top three.

Figure 4-8a shows the most significant values influencing diversion results. Purity of material collected is the most significant influence on diversion, with the commercial area purity the most significant of the two. The importance of commercial purity seems reasonable given the majority of waste is generated in commercial areas. Interestingly the residential line indicates a strategy change as the purity approaches 65 percent - about one third unrecyclable content. The rainbow diagram shown in Figure 4-8b helps determine the purity where the strategy changes from curbside commingled to satellite drop-off. It appears the change occurs at about 69 percent purity. If the residential area cannot achieve at least 70 percent purity in material collected (i.e. less than 30 percent

nonrecyclable material), then satellite drop-off points will produce greater diversion. This would be very useful information to the program manager, particularly if contemplating a change in the existing program method.

The other significant factor for diversion result is the fraction of total waste from the commercial area. Again this seems appropriate given the model parameters of higher participation for residential than commercial methods. As the proportion moves towards equal generation in both areas, the diversion percentage increases.

Taken together, these results indicate that the preferred strategy is rather robust under changing conditions for the given values. It appears that there is little potential for market factors or uncertainty to significantly affect the outcomes. Based on these results, further analysis may provide additional insight to the outcome under different conditions.

Baseline Scenario Financial Result Sensitivity
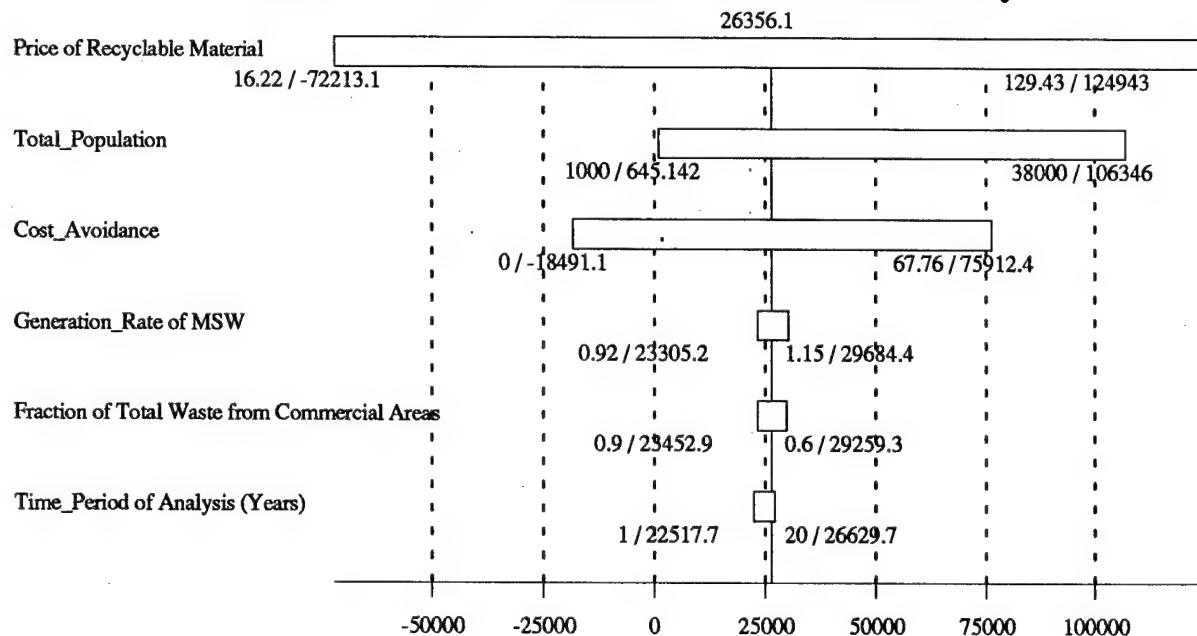
Figure 4- 7 Value Tornado Diagram - Financial Result (Baseline Scenario)

Baseline Scenario Diversion Percentage Sensitivity

21.6335

Purity of Commercial Curbside Commingled Collection

0.65 / 18.662   0.9 / 23.6145

Purity of Residential Curbside Commingled Collection

0.65 / 20.8141   0.9 / 22.3567

Fraction of Total Waste from Commercial Areas

0.9 / 21.3316   0.5 / 22.1366

Cost_Avoidance

67.76 / 21.6335

Estimated_Weighted_Price

129.43 / 21.6335

Generation_Rate

1.15 / 21.6385

19   20   21   22   23
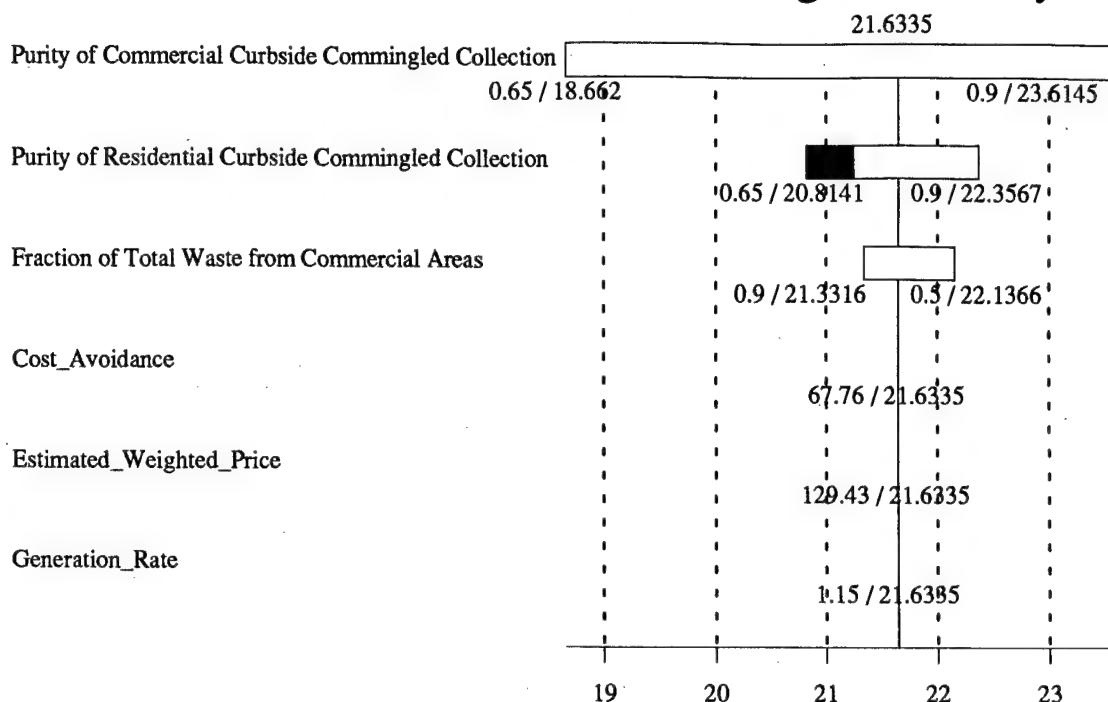
Figure 4- 8a Value Tornado Diagram - Diversion Percentage (Baseline Scenario)

Material Purity

Diversion Percentage

Residential Curbside Commingled

21.7-
21.6-
21.5-
21.4-
21.3-
21.2-
21.1-
21.0-
20.9-
20.8-
20.7-

Central Drop-Off

Satellite Drop-Off

0.66   0.68   0.7   0.72   0.74   0.76   0.78   0.8

Purity of Material Recovered
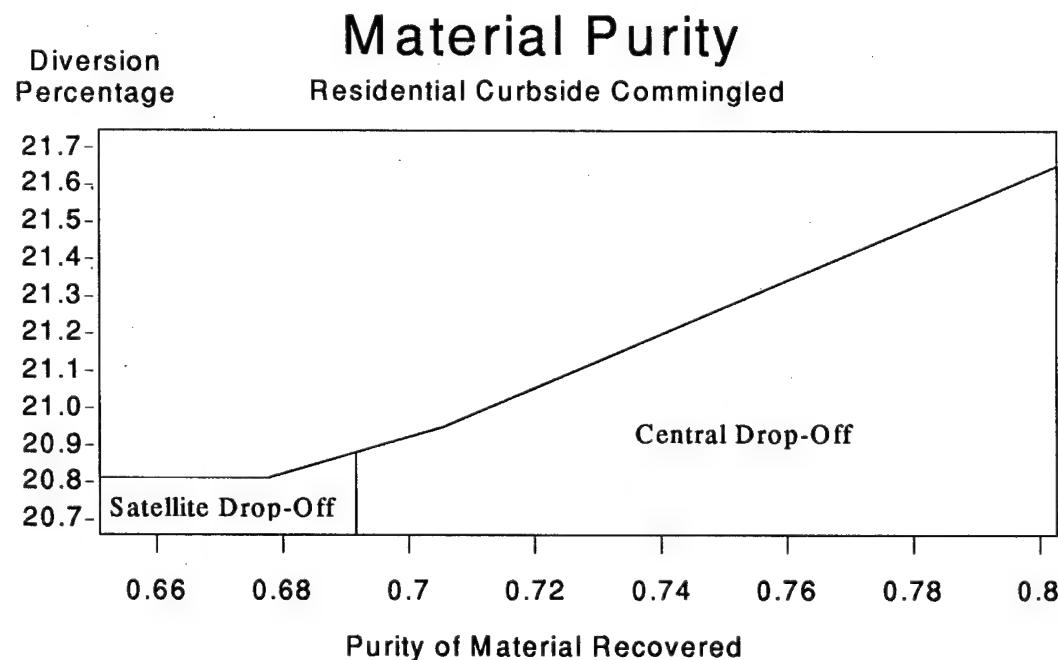
Figure 4- 8b Rainbow Diagram of Residential Purity

The uncertain events can also be compared using tornado diagrams. The financial result is shown in Figure 4-9a and the diversion percentage is shown in Figure 4-9b. In each figure, the base case represents all uncertainties at their expected values. The other lines consider only one uncertain event at a time, fixing all others at their expected value. The color change marks the 50th percentile of the respective uncertainty, with the ends of the bars marking the 10th and 90th percentiles respectively. Again, each of these diagrams considers the uncertainties based on the strategy that optimizes the objective (1-1 for financial, 3-3 for diversion).

Financial result (Figure 4-9a) is sensitive to all three uncertainties, but price is by far the most influential. Participation does have a minor impact on the financial result in that more material recovery will return more money when the recycling is profitable. Diversion is sensitive to the both residential and commercial participation (Figure 4-9b), but not price. Commercial uncertainty is more influential, but this is reasonable considering the majority of waste is generated in commercial areas. The uncertainty affects both objectives to different degrees, further illustrating the conflict between the two objectives.

The difference in strategies preferred depending on the objective, financial result or diversion percentage, was obvious in the figures and discussion above. Some way to combine these attributes into a measure of merit is needed. A utility function is one way. A utility function is a mathematical representation of the decision maker's preferences for certain outcomes of the attributes. By measuring the value of each outcome and
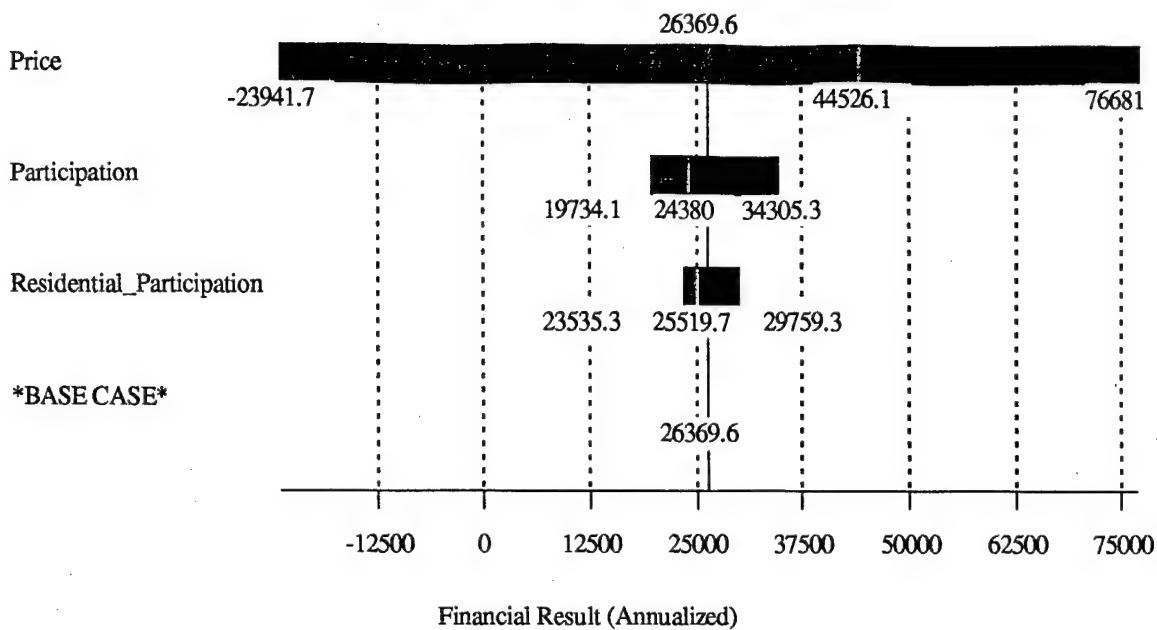
Figure 4- 9a Uncertainty Tornado Diagram - Financial Result
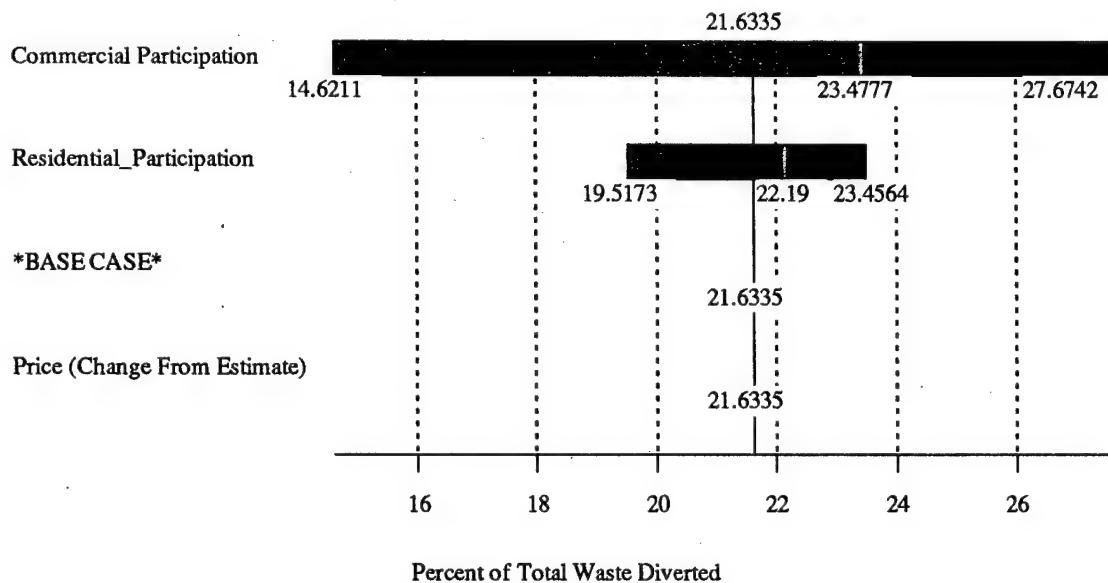
Figure 4- 9b Uncertainty Tornado Diagram - Financial Result

4-11

combining the results, multiple attributes can be combined into a single score allowing more discrete selection. However, the lack of a specific decision-makers' preferences and the almost certain differences in preferences encountered at installations throughout the Air Force make the utility approach cumbersome. Further, as decision makers change, the utility function needs to be reestablished. A more explicit method for evaluation and selection is appropriate, ideally one that would allow the decision makers preferences to be added without significant rework.

Frontier Analysis

Another way to examine the results is to look at a plot of the financial result vs. diversion. An efficient frontier can be established by connecting the points furthest from the origin in the desired direction, positive for both objectives in this case. These points are called *Pareto optimal or non-dominated*. By definition, there are no other solutions at least equal to the *Pareto optimal* points in every objective and better than the *Pareto optimal* points in at least one objective (Winston, 1994:809).

Connecting the points in a convex space theoretically means that any point on the boundary is possible, and is equally desirable to the decision maker. Any point not on the boundary is less than optimal. Analysis can be used to compare the strategies based on their distance from the optimally efficient frontier. This is left for future efforts. The presentation of strategies allows the decision maker (an installation commander) to make implicit tradeoffs. This approach avoids the development and assessment of utility functions which may be helpful when established, but would certainly differ between

4-12

installations. This approach allows this tool to be useful to a maximum number of installations with minimal change. Since only two attributes are used in this analysis, a plot of results will be helpful. The outcome values for the sixteen possible strategies are displayed in Figures 4-10 through 4-12. A combined plot (Figure 4-13) showing the region bounded by the worst case and best case frontiers defines the region of likely outcomes. The strategies are numerically coded for easy reference:

1. Centralized Collection
2. Satellite Collection
3. Curbside Commingled
4. Curbside Separated

The first number represents the commercial area strategy and the second is the residential area strategy. For example, strategy 1-3 represents central drop off in commercial areas, and curbside commingled in the residential areas.

Three levels of the results are presented: 5th, 50th and 95th percentiles. These percentiles represent three categories of risk attitude: risk averse, risk neutral, and risk seeking (Clemen, 1991:367). Consider the recycling program financial result to illustrate the risk attitudes. Risk averse decision makers will accept a small cost that is virtually certain rather than taking a chance to make a profit but possibly incur a large cost. Risk neutral decision makers will use the expected value for making the decision. Risk seeking decision makers will try to make as much money as possible. The risk seeker will forgo the certain small cost to have a chance of making a large profit while also risking a large cost result.

The conflict of diversion and profit is obvious in the results. More profitable strategies, ones towards the top and right of the graph, are also those that achieve less

diversion. The efficient frontier helps clarify this tradeoff by narrowing the choice to only

those strategies on the frontier. Only five strategies are optimal in the 5th percentile

analysis: 1-1,1-2, 2-1, 2-2, 2-3. These five strategies are on all three frontiers for the

baseline scenario. The drop-off strategies (1 and 2) are pervasive. The only curbside

strategy is commingled collection combined with satellite drop-off in commercial areas.

Strategy 3-3 is very close, but not on the frontier. Even if it were on the frontier, it is

unlikely to be selected unless the decision-makers' preference were weighted almost

entirely in favor of diversion, with very little importance place on profit. This extreme

preference would be unlikely.

Eight strategies are on the frontier in the 50th percentile analysis: 1-1,1-2, 2-1, 2-

2, 2-3 plus 3-1, 3-2, and 3-3. These strategies are on the 95th percentile analysis of the

baseline scenario as well. Curbside commingled collection (3) is more evenly represented

along with the satellite (2) and central drop-off (1) strategies.
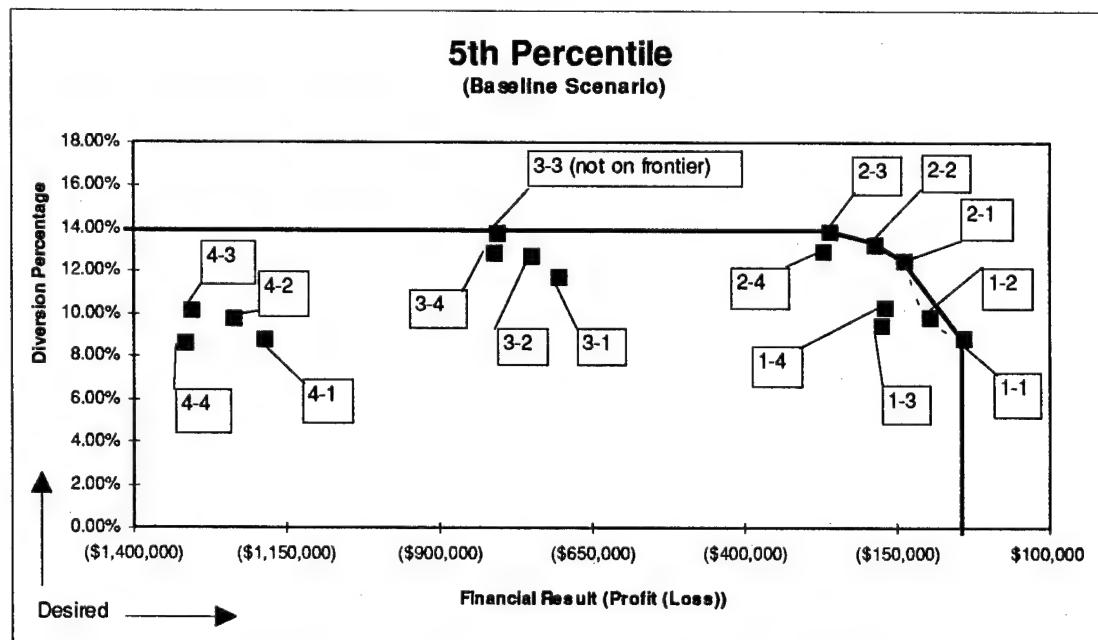
Figure 4- 10 Plot of Financial Result and Diversion

4-14
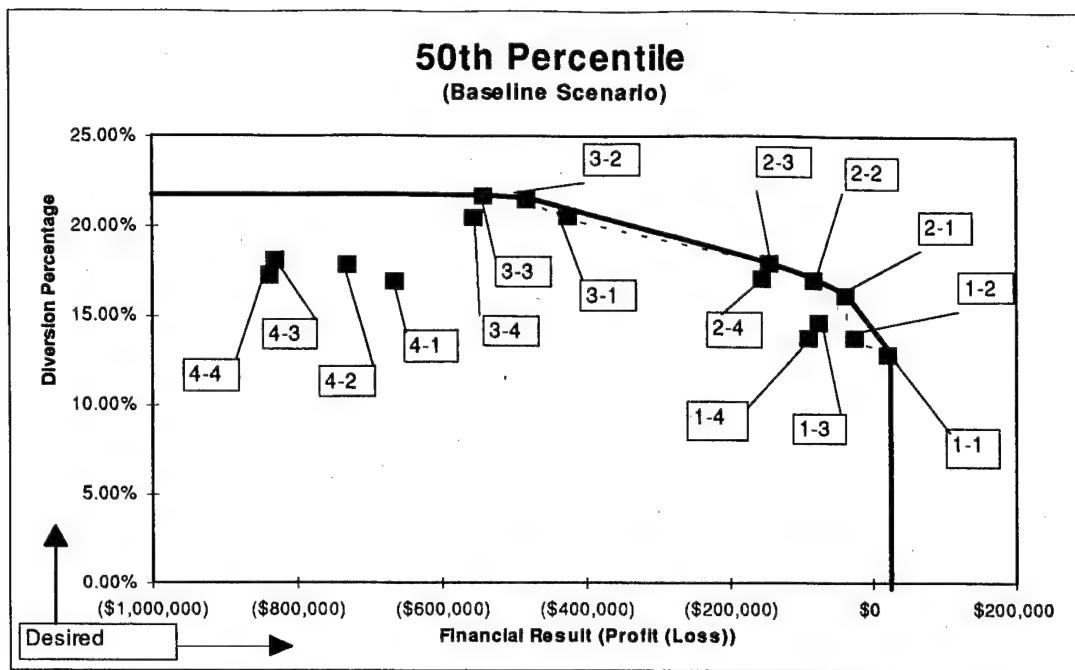
Figure 4- 11 Plot of Financial Result and Diversion
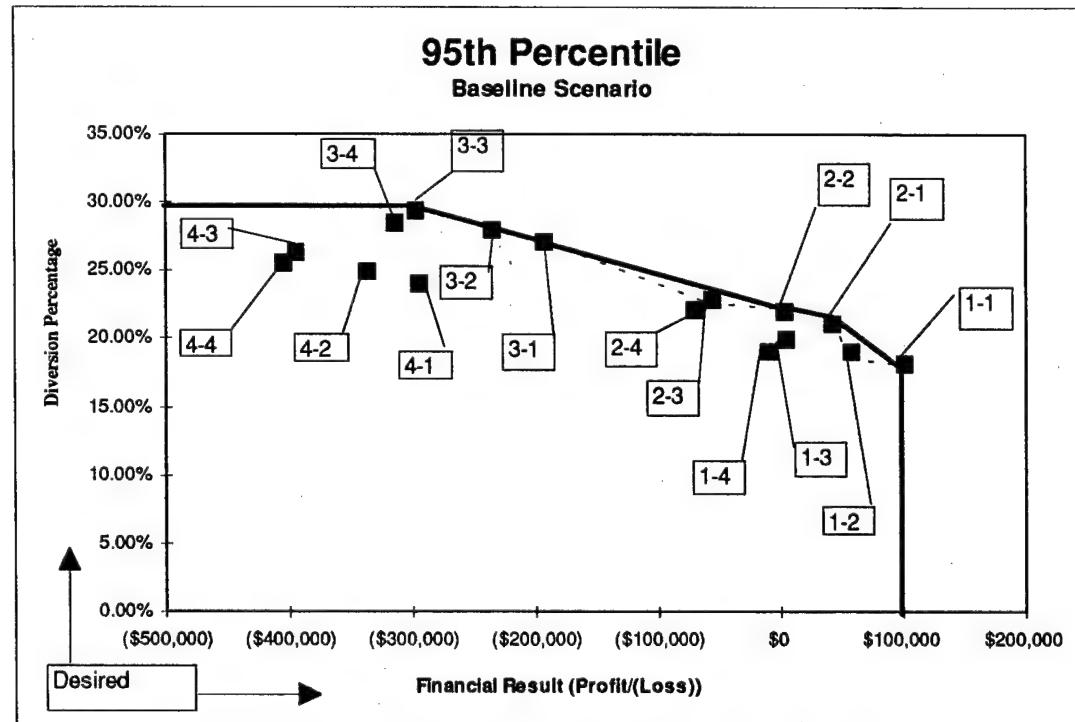
Figure 4- 12 Plot of Financial Result and Diversion

4-15

Diversion Percentage
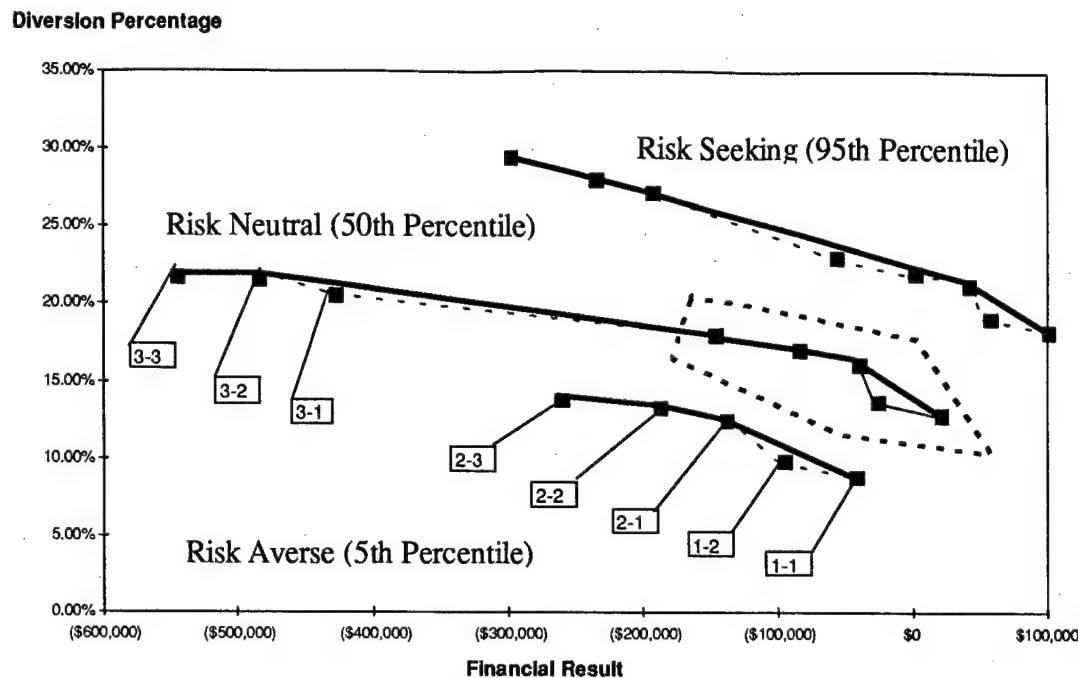
Figure 4- 13 Region of Likely Outcomes

The results show some distinct strategy dominance groupings. Method four (curbside separated) is never on the optimal frontier for any level of uncertainty. Method three (curbside commingled) is on the frontier in only one strategy at the 5th percentile, but in four strategies at the 50th and 95th percentiles. The shape of the frontier at strategies using method 3 indicates this would be a likely choice only when diversion is more important than financial result. Methods 1 and 2 are present in the five strategies appearing on all three frontiers. The shape of the frontiers in all three frontiers indicates these methods (1 and 2) would be selected when diversion and financial result are roughly equal in consideration or when financial result is more important than diversion in any amount.

4-16

The pattern within each group and overall is similar (Figure 4-14). This pattern is seen clearly in all of the frontier plots of the baseline results (Figures 4-10 through 4-12). This pattern seems to indicate that curbside separated methods are dominated by curbside commingled. The other methods (curbside commingled, satellite, and central drop-off) are nondominated, thus they are the feasible alternatives for consideration.
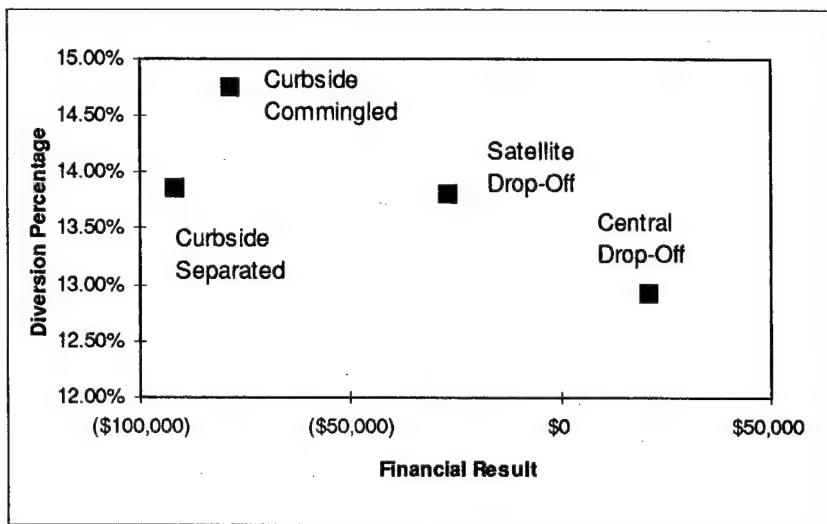
Figure 4- 14 General Method Pattern of Results

Threshold values may play a role in the decision maker's assessment. There are only four strategies that are profitable at the favorable 95th percentile; only one is profitable at the 50th percentile as well, 1-1. Only three strategies achieve over 25 percent diversion at the 95th percentile, all three use the curbside commingled method in commercial areas. The same three are the only strategies above 20 percent diversion at the 50th percentile frontier. Additionally only three other strategies achieve over 20 percent diversion in the 95th percentile, all using the satellite drop-off method in the commercial area.

Preference Inferences

The frontier changes shape, but the relative outcomes of the strategies are consistent across the range of uncertainty. The most likely candidates are those enclosed within the dotted region in Figure 4-13. These strategies are on the frontier at the 5th, 50th and 95th percentiles, so their optimality is fairly certain at nearly all levels of uncertainty. By analyzing these points the range of preference can be defined over which each strategy would be preferred. An enlarged plot of the five most likely strategies (Figure 4-15) is also used to eliminate strategy 1-2. Assuming a preference function that trades diversion for financial return linearly (p*financial result+(1-p)* diversion) where ($0 \leq p \leq 1$) holds true, the preference line would intercept strategy 2-1 before getting to 1-2 as it rotates counter-clockwise from complete financial preference to complete diversion preference. The preference indicated by the frontier points is illustrated in Figure 4-16.
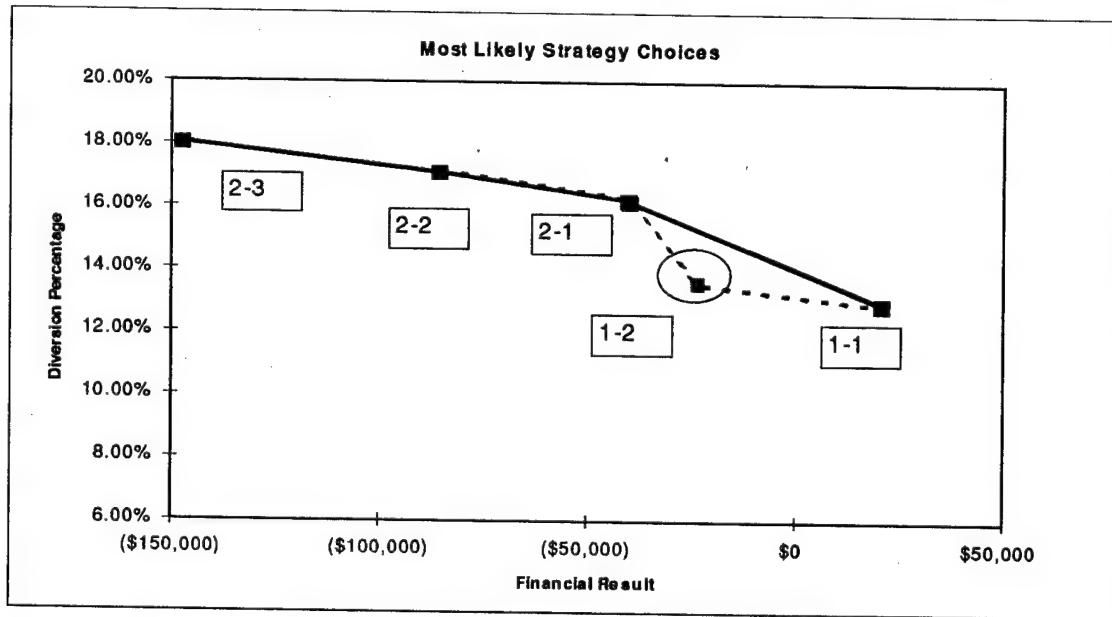
Figure 4- 15 Most Likely Strategies (50th Percentile)

The preference line is moved from right to left on the graph; the first point

intersected is the optimum strategy for the preference structure represented by the line. A

complete preference for financial result would be shown by a vertical line; conversely a

complete preference for diversion would be shown by a horizontal line. As the

intersecting line rotates between horizontal and vertical, it represents the infinite number

of preference weight combinations. Note that the region defined by the frontier points and

a linear preference function is convex. This convex hull will pass over some non-

dominated points that are not on the optimal frontier (This occurs with strategy 1-2,

shown in Figure 4-15) . The range of preference weights that would result in a particular

frontier point being selected can be calculated by the lines joining adjacent points on the
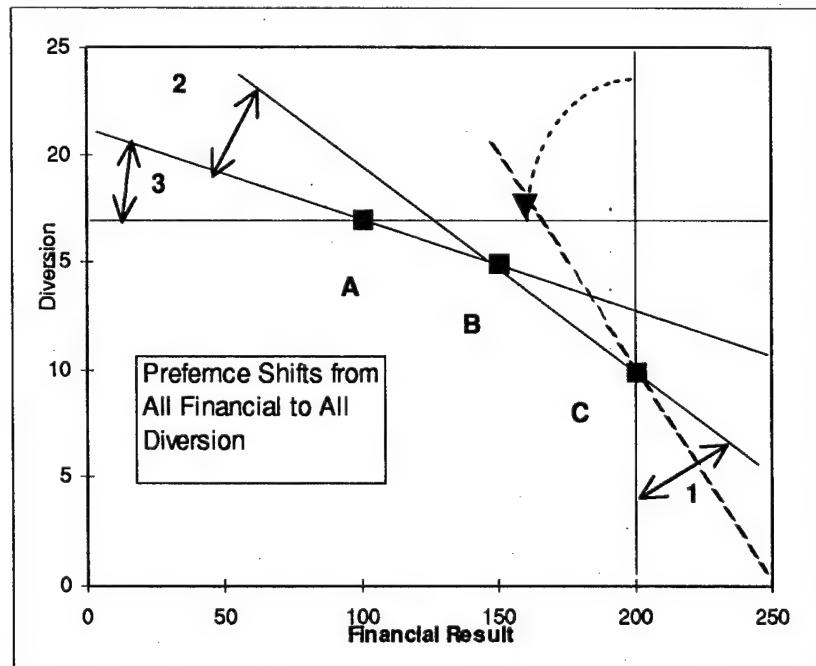
Figure 4- 16 Preference Inference from Lines of Intersection

frontier. A simple example is shown in Figure 4-16 in which 3 frontier points (A, B, C) are plotted. The regions of preference (1, 2, 3) are shown as well. Point C is preferred by lines in region 1, point B is preferred with lines in region 2, and point A is preferred with lines in region 3. The dashed line shown in Figure 4-16 indicates a preference weight of .67 for financial and .33 for diversion, favoring point C. The values for each preference region can be calculated using the coordinates of the two points.

Similar analysis is performed on the strategies identified earlier. By calculating the slopes of the lines joining these points, the preference weight combinations that would favor each strategy can be established. The preference weights for the strategies shown in Figure 4-15 are shown in Table 4-1. Strategy 1-2 is included to illustrate how the weights vary if the point is not on the frontier; the weights do not change consistently from point to point. With 1-2 excluded, the weights change continuously from

Table 4- 1 Preference Weights for Frontier Strategies

Strategy	Financial Result	Diversion	Slope of Frontier	Diversion Weight	Financial Result Weight	Preference (1% diversion per $10,000)
Upper Bound	-	-	0.000	1	0	Infinite
2:03	($147,637)	18.05%	-0.1063	0.881	0.119	7.40
2:02	($85,736)	17.12%	-0.150	0.823	0.177	4.66
2:01	($40,546)	16.24%	-0.195	0.758	0.242	3.14
1:02	($27,010)	13.83%	-1.78044	0.360	0.640	0.56
1:01	$20,431	12.95%	-0.5395	0.650	0.350	1.85
Lower Bound	-	-	Infinite	0	1	0

exclusively diversion to exclusively financial result. The weights also reveal a significant insight, strategy 1-1 (central drop-off in both areas) will be favored unless the diversion is at least twice as important as the financial result. Given the prevalence of curbside collection in the Air Force, one could surmise that many Air Force decision makers prefer

diversion at least twice as much as the financial result. The Air Force goal appears an important motivation in managing the recycling program.

Alternate Scenario Results

Two alternate scenarios, optimistic and pessimistic, were conceived based on changes in the baseline scenario (see Table 3-11). The efficient frontiers of these two scenarios are compared with the frontiers of the baseline scenario as shown in Figures 4-17 through 4-19. It is apparent that the financial result varies more than diversion from the pessimistic to the optimistic scenarios. The frontiers change shape between scenarios and percentiles, indicating that the tradeoff of financial result relative to the diversion percentage decreases as the uncertainty and scenarios become more favorable. The optimal strategy choices on the 5th percentile frontier (Figure 4-17) are spread over a
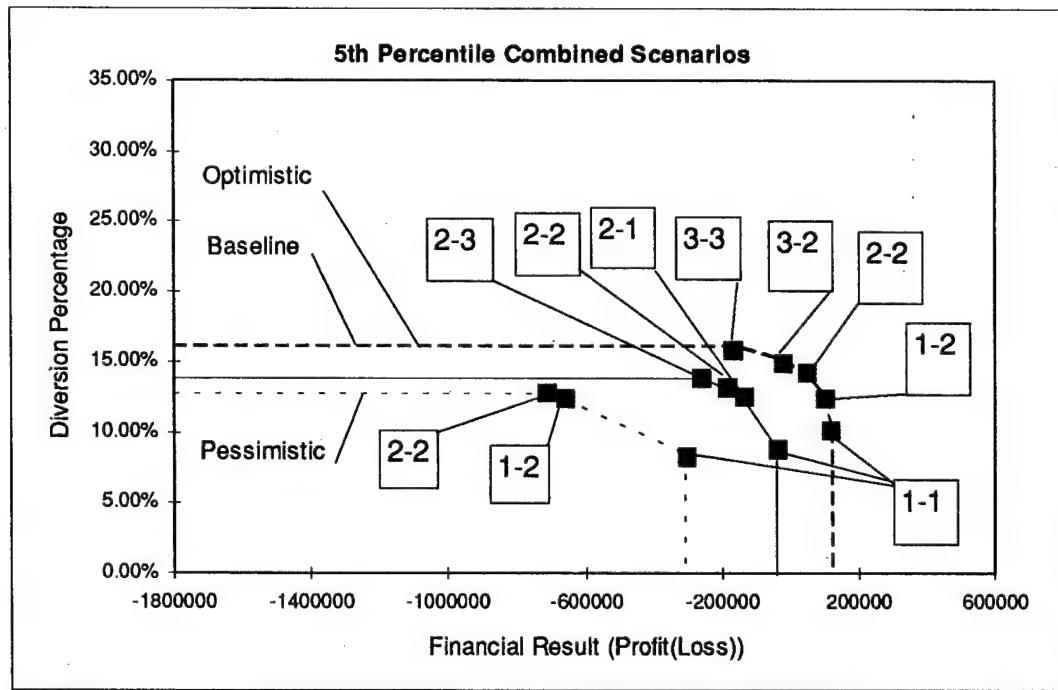
Figure 4- 17 Combined 5th Percentile Frontier
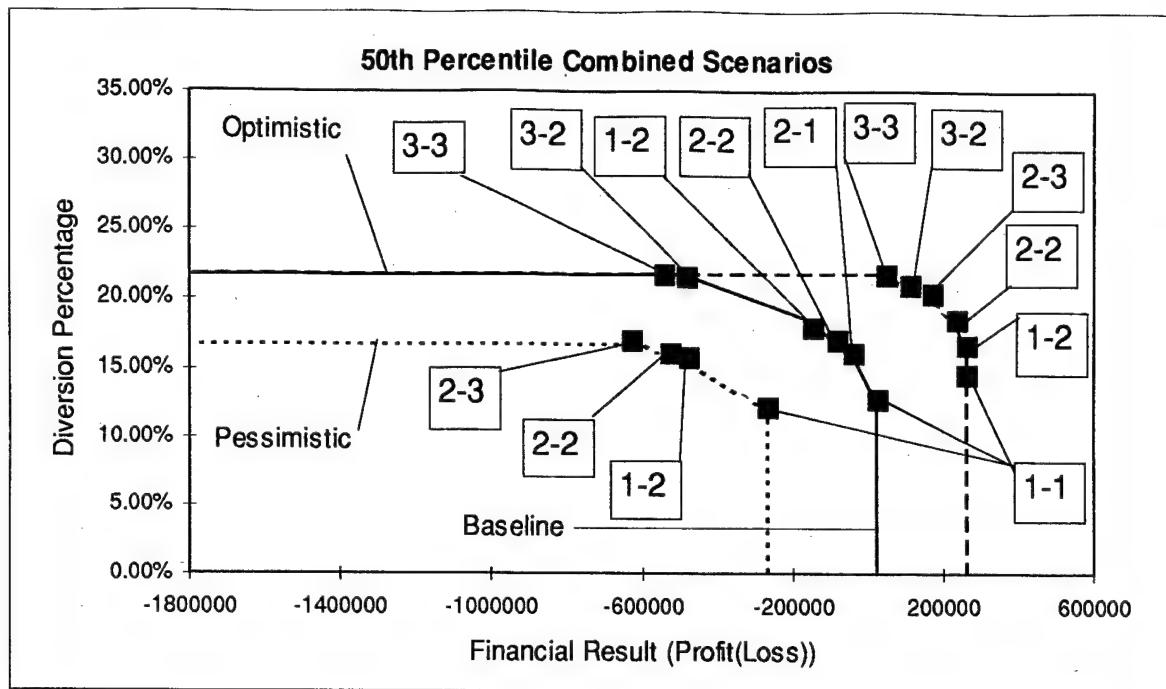
Figure 4- 18 Combined 50th Percentile Frontier
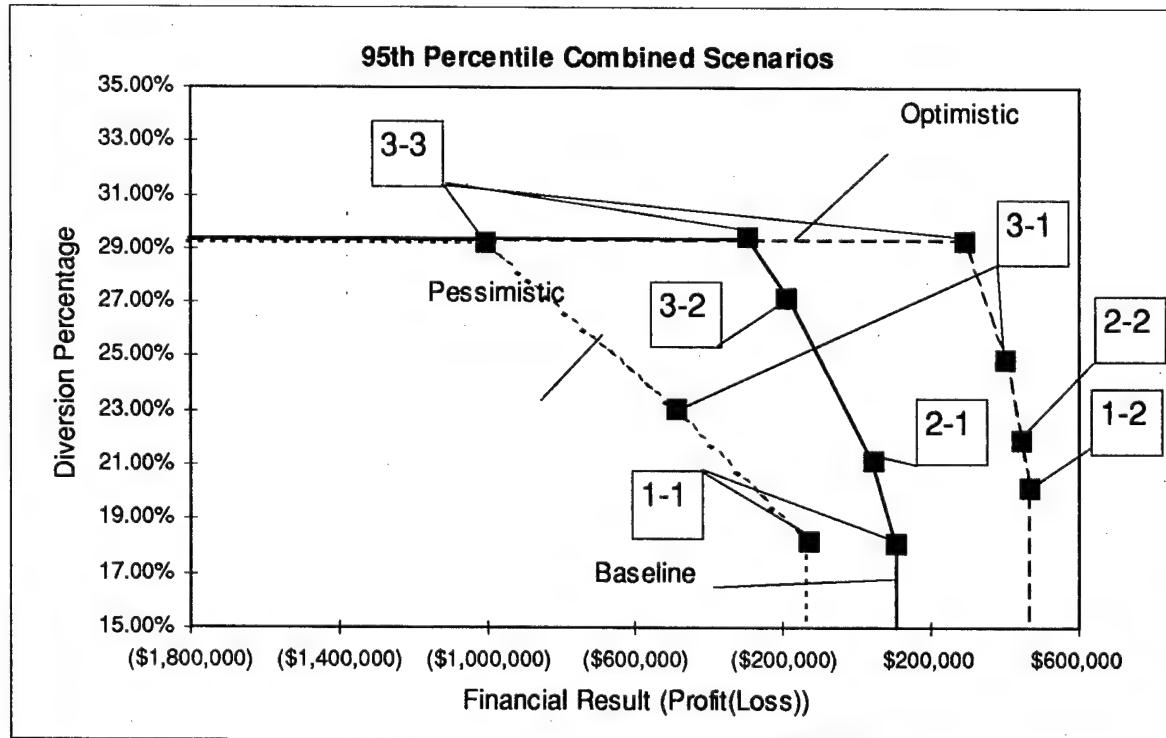
Figure 4- 19 Combined 95th Percentile Frontier

4-22

wider range of values than any frontier strategy on the 95th percentile frontier

(Figure 4-19).

The additional scenarios indicate that the frontier will change shape and position depending on the parameters, but the tradeoff of diversion against financial result is made in all cases. The frontiers are similar in shape and strategies for the scenarios at each of the three frontiers of interest. As conditions become more favorable, the frontiers progressively shift towards a profile favorable to financial results. The level of profit or loss financially becomes less variable relative to the diversion achieved as the conditions become favorable.

V. Conclusions and Recommendations

Introduction

This chapter will discuss conclusions drawn from this research. Analysis of the modeling results presented in Chapter Four is summarized. Practical implications for recycling program management are discussed. Recommendations for improving Air Force recycling programs are offered. Finally, topics of future research are suggested.

Summary of Results and Analysis

Recycling programs have two objectives: material diversion (material recovered from the waste stream) and profit. The Air Force has set a goal of reducing its landfill disposal by 50 percent from a 1992 baseline by 1997 (AFIT, 1995). Each installation can keep profits from recycling to use for health, safety, and recreation projects (USAF, 1994). The conflict of these goals is demonstrated in the model results. Increasing one performance towards one objective usually decreased performance towards the other objective.

The modeling of recycling programs focused on two distinct parts of an installation based on the different waste stream composition in each area: commercial (offices, maintenance areas, and duty related services) and residential (housing and recreation). One of four recycling methods are available for each area, the combination of methods is called a strategy. Sixteen strategies are available in the model. Each choice influences the participation of commercial and residential populations. Each strategy has associated cost

and material diversion implications. Participation rates and prices for diverted material are beyond the control of the base. They are modeled using triangular probability distributions based on estimates found in available literature. Total waste generated on base is estimated from the total population (personnel assigned plus dependents in housing). Eight materials are included in the model: paper, cardboard, glass, compostable waste, steel cans, other metal, and aluminum cans. Other information (number of housing units, time period of analysis, interest rate, estimated material price, and method costs) can be changed to customize the model to a particular installation.

The amount of each material diverted is calculated from the information in the model to determine total diversion and financial result. Financial result is measured in two ways. First, the material is sold at an uncertain market price. Second, the material diverted avoids the cost of disposal. The cost avoidance can be an important part of the financial analysis. If waste management services are provided by contract, the contract should be structured to allow recycling to reduce waste disposal costs.

Achievement of the goals is balanced at some compromise level. This level of compromise may not be explicitly understood by the decision maker. Further, the decision maker (installation commander) will change at an Air Force installation approximately every two years. By plotting the two results, they can be evaluated without combining them. An efficient frontier is made by connecting the extreme points (those farthest from the origin) points as shown in Figures 4-10 through 4-12. The frontier shows the best strategies from which to choose. The decision maker's preference's are not needed to determine the frontier. This is a useful way to narrow the choices without bias. The

preferences that dictate choosing a particular strategy can be bounded by analyzing the frontier (Chapter Four, Preference Inferences).

The frontiers for recycling programs show that drop-off methods should be preferred more than curbside methods, particularly if the decision maker is risk averse and values profit more than diversion. If the decision maker is risk seeking, curbside programs become more preferred. They are also the preferred when diversion is more important than the profit or cost, but only if diversion is at least twice as important as financial result (see Figure 4-17).

Five strategies are on the frontier at the 5th, 50th, and 95th percentiles of the analysis, all are drop-off in commercial areas and all but one use drop-off for residential areas. Three more curbside strategies are on the 50th and 95th percentile frontiers, and would be considered by decision makers who value diversion much more than financial result.

Two additional scenarios were developed for the entire model (Table 3-10). The results of these scenarios show that it is unlikely that recycling will achieve more than 30 percent material diversion. Also, the range of financial result is much greater than the range of diversion for each scenario. The financial result is more uncertain than the diversion result over the range of the parameters of the model varied in the three scenarios. As the model parameters range from pessimistic to optimistic, the range of diversion decreases while the range of financial result increases.

The additional insights, such as those discussed above and in Chapter Four, would be valuable to an installation commander when considering alternatives for the recycling

program. The method presented allows the analyst to identify the most promising

alternatives while not presuming to understand the decision-maker's preferences. It also

allows subsequent analysis to be focused on a few alternatives, rather than the entire set.

Research Objectives

Recall the objectives of this thesis from Chapter One. The primary objective is to

create a decision analytic model of recycling at the installation level that will provide

recommended alternative strategies to the decision maker which most support the overall

MSW management goals and will enhance the MSW management model. Supporting

objectives related to the modeling effort are:

- Determine the basic values and influences of an installation recycling program.

- Determine all significant influencing factors for installation recycling programs.

- Explore the opportunity for the recycling model to provide stand-alone analysis in

  addition to supplementing the existing MSW management model (Muratore, 1995).

Primary Objective. The primary objective of developing a decision analytic model

of installation recycling was accomplished. The model provides useful analysis of

installation recycling by combining information from available literature and data from Air

Force reports. The model allows a range of analysis from explicit assessment of specific

strategies to a broader comparison of alternatives (as presented here). The structure of

the model allows adaptation to local conditions through the various parameters (such as

total population, costs, prices, and economic analysis factors).

Supporting Objectives. The basic values and influences of an installation recycling program were developed through the modeling process. Among these are parameters such as waste generation and composition, costs, and recycling method performance characteristics. Influences, such as the uncertainty of the level of participation by base population and the selling price of materials, were important as well. The lack of the decision maker's preference structure is not a hindrance to the modeling effort; the feasible frontier approach to analyzing the results may help the analyst present more concise alternatives to a decision maker based on this model.

Significant influencing factors for installation recycling programs were identified in Chapter Four (Figures 4-7, 4-8a,4-9a and 4-9b). Factors influencing diversion percentage, in order from more to less, are:

1. Uncertainty of commercial participation
2. Purity of commercial area material recovered
3. Uncertainty of residential participation
4. Purity of commercial area material recovered
5. Proportion of waste from the commercial areas of the base.

The factors significantly influencing the financial result, in order from more to less, are:

1. Selling price for recovered materials
2. Total population (more people generate more waste)
3. Uncertainty of material selling price
4. Including cost avoidance in the financial result

The installation can control the diversion influences more than the financial influences. The total population of a given base is known, and not necessarily an influence on the program. Cost avoidance is the only other financial factor within an installation's ability to control. Conceivably, the purity of material collected and the participation are within the ability of the installation to control, making the diversion percentage more

controllable than the financial result. This type of sensitivity analysis and elimination of insignificant effects further helps the analyst and installation recycling program manager focus attention on the aspects of the program that are within their capability to control and will have a significant effect on the result.

The opportunity for the recycling model to provide stand-alone analysis in addition to supplementing the existing MSW management model is demonstrated. The model indicates that within reasonable levels of performance recycling alone is not likely to achieve the Air Force's solid waste management goal of reducing landfill disposal by 50 percent. This is consistent with the findings of previous research (Muratore, 1995) which found the optimum waste management strategy to be a combination of methods. The structure of the model allows for adaptation to conditions at any installation based on information available to the recycling program manager.

Decision Analysis Insights

Using efficient frontiers and dominance to narrow the choices is an effective way to analyze problems, particularly when the decision-maker's preference structure is not known. This should be extremely useful at the Air Force level where one is frequently challenged with solving problems without the decision-maker's preference structure. It is also likely that the decision maker will change frequently as commanders are reassigned. This approach reduces the analysis needed for a new decision maker.

This analysis method was well suited for this problem, there were only two outcome values of interest: financial result and diversion percentage. The intuitive

approach would be easily understood by decision-makers unfamiliar with sophisticated decision analysis methods. Results are easily plotted in two dimensions. However, problems with three objectives become more difficult to plot. The intuitive appeal is lost with any more than three objectives, although multicriteria decision analysis techniques are available. The ability to infer preference weights from the frontier (see Figure 4-17) helps the analyst narrow the focus of further investigation to the strategies most likely to yield the better results. It also allows the analyst to bound the preference weight values which favor each frontier option.

This approach may also be useful given the iterative nature of decision analysis. Framing the problem and eliminating the improbable choices provides a basis for further refinement of the problem through interaction with the decision-maker. This helps focus time and effort on the important issues of the problem.

Recycling Recommendations

Air Force recycling programs are faced with two conflicting objectives. The conflict between the institutional goal of diversion from landfill disposal and the installation profit incentive is readily observed in the results. Maximum diversion (which is the goal according to Air Force guidance (USAF,1994)) can mean high cost and minimizing cost does not result in maximized reduction of landfill use. The result is usually a compromise solution that balances the two objectives at some intermediate satisfactory level. The frontier explicitly identifies preferred strategies and the required trade-off implicit for each.

The commercial strategy appears to characterize the overall result since most waste is generated in commercial areas. The decision-maker's preference is reflected primarily in the commercial strategy preferred. Minor distinctions reflected in the residential strategy will affect the exact preference, but the general values are very easily inferred from one strategy selection by the decision-maker.

Cost avoidance should be included in the measurement of financial results. Cost avoidance is the single most important variable influencing the financial result within the control of installation management (see Figure 4-7). Contracts, financial management systems, and performance measurements should be changed or established to capture the cost avoidance as part of the total program. Changing to weight-based refuse service is one example which should be implemented at Wright-Patterson AFB. During the research, I discovered that an estimated-volume refuse contract is used at Wright Patterson. This type of contract does not allow the reduction of refuse cost for the amount of material recycled, effectively paying for services not needed.

Connections to Past Research

This thesis is based on the work of John Muratore's (1995) thesis. It complements his model of waste management options by further developing a more realistic and comprehensive recycling model. This research complements the existing body of knowledge in waste management by proposing a framework for alternative analysis. The decision model synthesizes goals and constraints. The results can then be displayed to allow the decision-maker to make a more informed decision.

Recommendations for Future Research

Several aspects of this research could be carried further. Air Force leadership at squadron, group, wing, and perhaps MAJCOM level could be surveyed to determine if bounds exist to the realistic range of preference weighting. This researcher would hypothesize that weights beyond 80/20 (four to one preference) in either direction would not be selected. The impact of this narrowing of feasible alternatives could be useful in screening possible alternatives early in the analysis process as discussed earlier (such as curbside sorted methods that are dominated, shown in Figures 4-10 through 4-12).

The costs and revenues used in the model are based on data available in the literature. Validation of each Air Force installation's cost and revenue data could determine if they are significantly different than the information available based on widely varied public sector programs. Several installations are recognized for their recycling programs, these should be the first reviewed since they probably have the most data available. Investigation of these programs may identify or more accurately assess variables that could improve the model.

Further refinement of the model could be done based on validation at an installation. The effect of contract service compared to government employees could be an interesting study. However, the low budgets currently available combined with this analysis would seem to preclude substantial Air Force investment in waste management recycling infrastructure. The push for privatization is apparent in the waste management area; most bases contract their waste services (Carper, 1996). Services such as custodial,

grounds maintenance, and refuse have been contracted for many years. Installations that manage their waste in-house usually have extenuating circumstances such as prison labor or remote locations that are unusually favorable to the financial return.

The inference of preference from the efficient frontier is another topic that may warrant additional research. Use of a graphical tool such as the charts shown in this document may provide a reasonable approach for assessing decision-maker values and preferences, particularly at an early stage of the analysis.

Summary

The EPA's waste management hierarchy identifies source reduction as the best way to manage municipal solid waste (produce less of it). However, available data indicates that the Air Force generated as much waste per-capita in 1994 as it did in 1992 (AFCESA, 1996). Given this, the next best option for waste management is recycling.

Recycling is not going to solve all waste management problems for the Air Force but it has achieved significant results. However, the conflicting objectives of installation recycling programs lead to compromises. The decision analytic model developed attempts to present the inherent trade-offs in a clear way, allowing informed decision making without restraining the decision-maker's discretion. The modeling and analysis indicate that less aggressive methods of recycling municipal solid waste are a more even tradeoff of the goals of financial return and diversion.

Appendix A - Price and Cost Data Calculations

Inflation adjustments were based on the *Quantity and Price Indexes* (DoC, 1996). Cost

information was taken from Material Profiles in Waste Age magazine in the indicated year.

Month/Year	Price Index	Inflation adjustment
Jan-92	100.0%	109.5%
Jan-93	102.6%	106.7%
Jan-94	104.9%	104.4%
Aug-94	105.2%	104.1%
Jan-95	106.7%	102.6%
Jul-95	107.3%	102.1%
Jan-96	109.0%	100.5%
May-96	109.5%	100.0%

Figure A-1 Inflation Adjustment Factors

Material	Year	Infation Adjustment	Recycling cost estimates Collection(assumed curbside commingled) low	avg	high	Processing low	avg	high
Office Paper			$ 60.00				$ 33.59	
Steel Cans	1993	106.7%	$ 217.00	$ 265.00	$ 309.00	$ 30.22	$ 67.53	$ 125.64
Newspaper	1994	104.4%	$ 60.00	$ 75.00	$ 90.00		$ 33.59	
HDPE	1992	109.5%	$ 900.00	$ 1,150.00	$ 1,400.00		$ 187.95	
Glass	1992	109.5%	$ 54.00	$ 65.00	$ 77.00		$ 50.02	
Compostable	1993	106.7%	$ .10.00	$ 80.00	$ 130.00	$ 20.00	$ 100.00	$ 300.00
PET	1992	109.5%	$ 987.00	$ 1,200.00	$ 1,401.00		$ 183.84	
Aluminum	1992	109.5%	$ 526.00	$ 635.00	$ 743.00		$ 143.41	
Corr Cardbd	1992	109.5%	$ 60.00	$ 75.00	$ 90.00		$ 42.99	

Figure A-2 Cost Calculations

Price Information is based on Recycling Times (Petrush, 1995; Egan, 1996)

		Nov-95			Oct-96	
Material	Low	Medium	High	Low	Medium	High
Commercial Mixed Paper	$0	$75	$150	$0	$43	$85
Residential Mixed Paper	$0	$35	$70	($15)	$8	$30
Plastic	$80	$190	$300	$40	$140	$240
OCC	$5	$33	$60	$30	$53	$75
Compostable	($15)	($10)	($5)	($22)	($13)	($3)
Aluminum Cans	$1,100	$1,250	$1,400	$800	$1,000	$1,200
Steel Cans	$30	$63	$95	$30	$58	$86
Metal (Misc)	$0	$120	$240	$0	$200	$400
Glass	$0	$33	$65	$0	$43	$85

Figure A-3 Price Data for One Year Period

Summary Prices shown in Figure A-4 are the average of the November 1995 and October 1996 prices from A-3 above for the respective category (low medium, and high).

Summary Prices (Recycling Times, 1995,1996)			
Material	Low	Medium	High
Commercial Mixed Paper	$ -	$ 58.75	$ 117.50
Residential Mixed Paper	$ (7.50)	$ 21.25	$ 50.00
Plastic	$ 60.00	$ 165.00	$ 270.00
OCC	$ 17.50	$ 42.50	$ 67.50
Compostable	$ (18.50)	$ (11.25)	$ (4.00)
Aluminum Cans	$ 950.00	$ 1,125.00	$ 1,300.00
Steel Cans	$ 30.00	$ 60.25	$ 90.50
Metal (Misc)	$ -	$ 160.00	$ 320.00
Glass	$ -	$ 37.50	$ 75.00

Figure A-4 Recycled Material Prices

Appendix B - ACC Recycling Data Report Worksheet

Total Solid Waste Disposed, Base (tons)   _____ tons
Total Solid Waste Disposed, MFH (tons)   _____ tons
Total Solid Waste Incinerated (tons)   _____ tons

                Total: _____ tons

Recycled Materials:

Material		
Aluminum cans	_____	tons
Steel cans	_____	tons
Cardboard	_____	tons
Newspaper	_____	tons
High grade paper	_____	tons
Glass	_____	tons
Plastics	_____	tons
Wood	_____	tons
Ferrous metals	_____	tons
Non-ferrous metals	_____	tons
Composting (yard waste)	_____	tons
Tires	_____	tons
Used oil	_____	tons
Lead acid batteries	_____	tons
Others (be specific):	_____	tons
	_____	tons
	_____	tons

                Total: _____ tons

Program Expenses:

Contract costs	$ _____
Equipment Costs	$ _____
Manpower Costs	$ _____
Facility expenses	
Construction	$ _____
Utilities	$ _____
Total Expenses	$ _____

Revenues from sales $ _____

Appendix C - DPL Software Annotations

Decision: Recycling Method

The commercial area decision for recycling strategy

Value numbers represent the purity of material collected via the given method

Decision: Residential Recycling Method

The residential area decision for recycling strategy

Value numbers represent the purity of material collected via the given method

Decision: Existing Method

Used to calculate capital investment costs in current dollars (present value).

If decision continues existing method, then assume the equipment is half through useful life, and replacement equipment is needed in (useful life/2) years.

If decision changes from existing method, then new equipment must be aquired now and (useful life) years in future.

Using "if" statements and 0,1, or 2 multipliers; the present value of equipment purchases needed can be calculated based on the time period and existing method.

For example, the Central-Central-Yes branch is shown below. Central dropoff equipment should last about 10 years. If the time period is less than (useful life/2) or 5 years, no new equipment will be needed; conversely if the time period is 12 years (or any number over 5 but less than 15) then replacement equipment will be needed once with a present value of $5500.   If the time period is 16 or more years then replacement equipment will be needed twice with a present value of 2*$5500.

if(Time_Period<5,0,if(Time_Period<15,1,2)*5500

Single Payment Compound Amount Formula (Fabrycky, 1991:42)
$F=P(1+i)^n$

Chance Event: Participation

Triangular Distributions used around the various participation estimates found in literature.

Traingular distribution is used since little definitive information was found regarding the distribution of participation. At best a low, high, and "average" rate was found. Average rate depends on the definition of participation; in one case participation is any set out at all on at least half of the collection days or bringing any material to a drop off site. In another article, participation was measured at three levels over eight weeks by measuring set-outs: at least once,

at least four times, or all eight times in the eight week period.

Chance Event: Price

The price uncertainty is reflected in a multiplier against the total revenue

used 50% to 150% range of current price based on literature

Value: Waste

Waste generation based on combination of:
residential @ 3.8 lbs/person-day (Tchobanoglous, 1993:138)
x 3.5 occupants per average USAF Housing unit
x # housing units x 365 days/yr

+ (plus)

Office generation @3.8 lbs/person-day (Source)
x 260 work days/yr

The amount of waste generated per person assigned to the base (tons/person-year)
based on regression analysis of 1994 Air Force Data. The regression analysis is
discussed in the thesis document.

Value: Paper

Typical for commercial material value nodes:

Diverted amount of given material calculated by:
  Material Fraction (of total commercial waste stream) x total waste x
  Commercial Fraction x Participation x Purity (Method) x likelihood factor
  (tendency of public to recycle that particular material - based on Simmons, 1990
  and Porter, 1996).

Value: Commercial Diversion

Sum of each of the eight material value nodes, in tons.

result is the total tonnage of commercial MSW diverted (recycled) by
the given strategy and participation levels.

This is added to the residential diversion to determine total diversion.

Value: Cost

Combines the commercial, residential, and existing method (capital)
costs (in current dollars, or present value).

Value: Revenue

Calculates the present value of the expected revenue from sales of recovered material using the interest rate and time period values given elsewhere.

This assumes that the revenue will remain constant (in inflation adjusted dollars) for the time period of the analysis.

Value: Commercial Employees

This node indicates the total number of military and civilian assigned to an installation. It is used to calculate total waste generated and equipment needed for the commercial area recycling strategies.

Value: Housing Units

Used to calculate equipment needed for the residential area strategy options such as number of satellite collection sites and number of curbside bins.

Value: Cost Avoidance

The cost avoided by recycling or otherwise diverting waste from current disposal method.

This cost may or may not be recoverable by the base and is therefore one of the items of interest in this research.
    For example, the existing refuse contract at
Wright Patterson AFB is based on estimated volume of available containers, regardless of whether that capacity is actually used. WPAFB pays to dispose of a given amount of waste whether or not it actually does. In this case cost avoidance would not be an appropriate consideration in the financial result.
    However, many other bases use weight based contracts that charge based on actual quantity disposed. In this situation, the cost avoidance is real, and is an appropriate consideration in the financial result.

Value: Respaper

Typical for residential material fractions shown in these value nodes

Diverted amount of given material calculated by:
 Material Fraction (of total commercial/residential waste) x total waste x
 Residential Fraction x Participation x Purity (Method) x likelihood factor
 (tendency of public to recycle that particular material - based on Simmons, 1990
 and Porter, 1996).

Value: Commercial Fraction

The proportion of all waste that is generated by commercial area activities.
Extracted From Air Force Civil Engineer Support Agency Data Report, 1994

<u>Value: Residential Fraction</u>

The proportion of all waste that is generated by residential area activities.
Extracted From Air Force Civil Engineer Support Agency Data Report, 1994

This node is calculated as (1-commercial fraction), thus all waste is attributed to
one of the two areas.

<u>Value: Residential Diversion</u>

Sum of each of the eight material value nodes, in tons.

Result is the total tonnage of residential MSW diverted (recycled) by
the given strategy and participation levels.

This is added to the commercial diversion to determine total diversion.

<u>Value: Diversion</u>

Sum of commercial and residential diversion value nodes, in tons.

Result is the total tonnage of MSW diverted (recycled) by
the given strategy and participation levels.

<u>Value: Financial Result</u>

Calculates the uniform annual cost of the net result (revenue-cost).

The formula use is shown below with the model variable names included:

((Interest_Rate*(pow(1+Interest_Rate,Time_Period)) /
   ((pow(1+Interest_Rate,Time_Period)-1)))*(Revenue-Cost))

the formula is the Equal Payment Series Capital Recovery Formula
(Fabrycky, 1991:44)

$A = ((i*(1+i)^n) / ((1+i)^n-1)) *P$

<u>Value: Diversion Percentage</u>

Percentage of total waste diverted by recycling. Calculated by dividing
total diversion (tons) by waste (tons) to yield decimal amount (i.e. .42108 or 42%)

<u>Value: Residential Collection Cost</u>

The average cost per ton for collection of recyclable materials
by the indicated residential area recycling method.

This is calculated as the weighted average of all materials multiplied by their respective costs per ton and respective fractions of recyclable material.

Value: Residential Sorting Cost

The average cost per ton for sorting and preparing for sale recyclable materials by the indicated residential area recycling method.

This is calculated as the weighted average of all materials multiplied by their respective costs per ton and respective fractions of recyclable material.

The curbside separated sorting/processing costs are decreased 10% from curbside commingled due to the sorting that occurs during collection.

Value: Commercial Collection Cost

The average cost per ton for collection of recyclable materials by the indicated commercial area recycling method.

This is calculated as the weighted average of all materials multiplied by their respective costs per ton and respective fractions of recyclable material.

The Curbside separated costs are estimated to be 110% of the curbside commingled costs based on ratio of average stops per day for respective methods: 181 commingled to 165 for separated (Siegler, 1996:16). 181/165 = 1.096 ~ 1.10 or 110%.

Value: Commercial Sort Cost

The average cost per ton for sorting and preparing for sale recyclable materials by the indicatedcommercial area recycling method.

This is calculated as the weighted average of all materials multiplied by their respective costs per ton and respective fractions of recyclable material.

Value: Commercial Cost

The sum of the commercial collection and sorting costs.

Calculates the present value of the expected costs of collecting and sorting recovered material using the interest rate and time period values given elsewhere.

This assumes that the costs will remain constant (in inflation adjusted dollars) for the time period of the analysis.

Value: Residential Cost

Calculates the present value of the expected costs of collecting and sorting recovered material using the interest rate and time period values given elsewhere.

This assumes that the costs will remain constant (in inflation adjusted dollars) for the time period of the analysis.

<u>Value: Estimated Weighted Price</u>

Combined price of each material times its fraction of total ton of collected material

<u>Value: End</u>

Dummy node used to bring influence diagram to ending node.

Can also represent the point at which utility functions can be applied to
the values to combine them into a single measure of performance.

<u>Value: Time Period</u>

The number of periods (years) over which the recycling strategy decision will
be analyzed.

This is used primarily in the financial calculations. It is also used to trigger
costs of purchasing replacement equipment at some time in the future.

<u>Value: Interest Rate</u>

Used in financial result calculations.

Sensitivity analysis is used to determine whether interest rates (within reasonable
ranges) affect the preferred strategy.

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Vita

Captain Gregory Williams was born 5 May 1966 in Pittsburgh, Pennsylvania. He graduated from Stephen T. Badin High School in 1984 and attended the University of Cincinnati in Cincinnati, Ohio. He was commissioned on 9 June 1990 and was conferred a Bachelor of Architecture degree the next day. His first assignment was to the 56th Civil Engineering Squadron at MacDill Air Force Base in Tampa, Florida as a design architect. He also served as Chief of the Simplified Aquisition if Base Engineering Requirements Element and Chief of the Maintenance Engineering Element. He entered the School of Engineering, Air Force Institute of Technology in May 1995. His next assignment is to the Air Combat Command Civil Engineer Staff at Langley Air Force Base, Virginia.

Captain Williams is married to the former Jane Elizabeth Colee of St. Augustine, Florida since 12 November 1994. They have a daughter, Emily.

Permanent mailing address: 94 Avon Drive
 Hamilton, Ohio 45013

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13. ABSTRACT (Maximum 200 words)

The United States Air Force requires each installation to operate a municipal solid waste recycling program. Two conflicting objectives, waste material diversion and financial result, are established for the program. Reducing landfill disposal is the primary objective, but the incentive for profit is strong because each installation can retain profits from the program. Installations can be divided into two distinct areas, commercial and residential, based on the waste stream composition and funding. Structuring of the recycling program is often done in an ad-hoc manner. A decision support model was developed to evaluate four methods for each area. The model combines available Air Force data and information from research literature to determine the results of sixteen strategy combinations. The important variables affecting the results are determined through sensitivity analysis. The results are used to establish an efficient frontier of preferred strategies. The frontier illustrates the trade-offs of each strategy. The frontier can be also be used to inform decision makers prior to final strategy selection and determine preference values which would favor a given strategy. The value free analysis provides an objective foundation for presentation to a decision maker with unknown or changing preference values. The model provides valuable insight into the performance of recycling strategies as part of an overall waste management plan.

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